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RECENT AND MIOCENE CARBONATE
SEDIMENTS FROM INDONESIA
(IN TWO VOLUMES)

BY

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VOLUME I

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Summary

Mapping and sediment sampling in reefs of the Pulau Seribu group (south-west Java Sea) shows the existence of ten physiographic zones and subzones represented by seven lithofacies. Reefs in the northern part of the archipelago are smaller, more closely spaced and morphologically simpler than those in the south. This pattern is attributed to differences in subsidence rate. A three-dimensional model is proposed for the evolution of these reefs but borehole data are required to test this model.

Miocene limestones are described in detail from hydrocarbon reservoirs in the Batu Raja Formation of the same area. Brief comparisons are made with surface outcrops of approximately coeval carbonate developments. The lithofacies developed within these limestones reflect variations in hydrodynamic regime and basement topography. Eleven diagenetic processes affected the Batu Raja limestones and the distribution of these is primarily related to sealevel fluctuations. Early diagenesis was marine and characterised by micritisation and precipitation of fibrous and bladed cements. Dolomitisation occurred in the mixed-water zone and its variable intensity is attributed to the configuration of the carbonate body relative to this zone. Subsequently the limestones were subjected to freshwater phreatic zone diagenesis resulting in dissolution and cementation, and at a late stage underwent burial compaction. Secondary porosity, which largely determines the suitability of these limestones as hydrocarbon reservoirs, is a function of the variable intensity of dissolution and cementation, burial compaction, dolomitisation and possibly micrite neomorphism.

The sedimentary processes that generated the Batu Raja buildups are inferred from comparisons with the Pulau Seribu and other Recent analogues. The contrasting pinnacle form of the Pulau Seribu patch reefs compared with the low relief of the Batu Raja buildups results from differences in the initial substrate topography and subsequent subsidence rate.

Keywords

Recent, Miocene, Indonesia, Carbonate, Diagenesis

LIST OF CONTENTS

	<u>Page</u>
<u>Volume I</u>	
List of Figures	xi
List of Tables	xv
List of Plates	xvi
List of Appendices	xx
CHAPTER 1 INTRODUCTION METHODS AND MATERIALS	1
1.1 Introduction and Objectives	1
1.2 Acknowledgements	4
1.3 Rationale Behind Site Selection in the Pulau Seribu and Collection of Samples	5
1.4 Sample Treatment	6
1.4.1 Recent Unconsolidated Samples	6
1.4.2 Recent Coral and Mollusc Samples	7
1.5 Sample Treatment; Miocene Cores and Outcrops, Selection of Material	7
1.6 Laboratory Analysis	8
1.6.1 Peels	10
1.6.2 Thin Sections	10
1.6.3 X-ray Diffraction	10
1.6.4 Cathodoluminescence	11
1.6.5 Scanning Electron Microscopy	11
CHAPTER 2 PULAU SERIBU	12
2.1 Introduction and Previous Work	12
2.2 Geographic, Tectonic and Climatic Setting	14

	<u>Page</u>
2.2.1 Regional Setting	14
2.2.2 Tectonics and Basement	14
2.2.3 Climate	16
2.3 Reef Anatomy	20
(a) Pulau Pari	21
(b) Pulau Kotok Kecil	22
(c) Pulau Petundang Kecil	22
(d) Pulau Ringit	23
2.3.1 Sand Cay	23
(a) General Characteristics	23
(b) Intertidal Subzone	24
2.3.2 Reef Flat	29
(a) Algal Flat	30
(b) Sand Flat	31
(c) Outer Colonised Moat	35
2.3.3 Lagoon	36
2.3.4 Shingle Rampart	38
2.3.5 Reef Slope	41
(a) Crestal Zone	41
(b) Reef Wall	45
2.3.6 Reef Base	47
2.3.7 Channel	49
2.4 Bioerosion	
(a) Sponge borings	
(b) Bivalve borings	
(c) Polychaete or sipunculid borings	
(d) Microborings	
(e) Encrusters	

	<u>Page</u>
2.5 Comparison with Recent Environments of Reef Growth in North and South Sulawesi, Indonesia	57
2.5.1 North Sulawesi	58
2.5.2 Sangkurang Archipelago	61
2.6 Recent Lithofacies in the Pulau Seribu	64
2.6.1 Introduction	64
2.6.2 Sediment Composition	69
2.6.3 Grain Size Distributions and Recent Lithofacies	76
(a) Coral mollusc packstone-rudstone lithofacies	79
(i) coral debris coral mollusc algal subfacies.	81
(ii) coral mollusc skeletal subfacies	83
(b) coralgal packstone-grainstone lithofacies	84
(c) coral cobble rudstone-grainstone lithofacies	85
(d) sparsely bioclastic bioturbated pellet-mud lithofacies	86
(e) winnowed coral mollusc grainstone lithofacies	87
(f) carbonaceous lithofacies	89
(g) silty clay impure carbonate lithofacies	90

	<u>Page</u>
2.7 Evolution of the Pulau Seribu	94
2.7.1 Introduction	94
2.7.2 Model for Reef Growth in the Pulau Seribu	95
(a) Initiation	95
(b) Early development	98
(c) Later development	101
2.7.3 Alternative Possibilities	103
2.7.4 Classification	106
 CHAPTER 3 MIOCENE CORES AND OUTCROPS	 110
3.1 Introduction	110
3.1.1 Location and Stratigraphy	110
3.1.2 Structure and Tectonism	113
3.1.3 Patterns of Deposition during the Early Tertiary in the Sunda Basinal Area	115
(a) Basement Controls	115
(b) Talang Akar Formation	115
(c) Batu Raja Formation	116
3.2 Depositional Facies: Batu Raja Formation	121
3.2.1 Coral Intraclastic floatstone-rudstone	123
(a) Distribution and thickness	123
(b) Texture	123
3.2.2 Bioclastic Foraminiferal packstone- wackestone	126
(a) Distribution and thickness	126
(b) Texture	126

	<u>Page</u>
3.2.3 Algal Boundstone	128
(a) Distribution and thickness	128
(b) Texture	129
3.2.4 Shelly Foraminiferal rudstone- floatstone	130
(a) Distribution and thickness	130
(b) Texture	130
3.2.5 Sandy Impure Grainstone	131
(a) Distribution and thickness	131
(b) Texture	131
3.2.6 Sparsely Fossiliferous wackestone-lime mudstone	132
(a) Distribution and thickness	132
(b) Texture	133
3.2.7 Coal	134
(a) Distribution and thickness	134
(b) Texture	134
3.2.8 Interpretation	135
3.3 Rajamandala Formation	139
3.3.1 Structure and Stratigraphy	139
3.3.2 Reefal Substrate	143
(a) Gunung Walat Quartzite	143
(b) Batuasih Marl	144
3.3.3 Lithofacies	145
(a) <u>Lepidocyclina</u> grainstone-packstone	145
(b) Coral debris floatstone rudstone	146
(c) Coral framestone	147

	<u>Page</u>
(d) Foraminiferal skeletal packstone- wackestone	148
(e) Recrystallised micritic limestone	150
3.3.4 Interpretation	151
3.4 Sengkang Basinal Area, South Sulawesi	154
3.4.1 Structure and Stratigraphy	154
3.4.2 Lithofacies	158
(a) Foraminiferal wackestone-packstone	159
(b) Shelly floatstone with clay beds	161
(c) Planktic foraminiferal packstone	161
(d) Recrystallised packstone interbedded with mudstone and siltstone	162
(e) Interbedded limestone-mudstone- sandstone	163
(f) Coral debris-shelly floatstone- rudstone	164
(g) Recrystallised limestone	166
(h) Shelly floatstone-packstone	167
3.4.3 Interpretation	168
3.5 Parigi Limestone Formation	171
3.5.1 Structure and Stratigraphy	171
3.5.2 Cisubah Shales	173
3.5.3 Lithofacies	174
(a) Coral skeletal floatstone interbedded with calcareous mudstone	174
(b) Micritised shelly coral packstone- floatstone.	174

	<u>Page</u>
(c) Coral rudstone-framestone	176
(d) Interlayered foliose coral framestone and foraminiferal floatstone	176
3.5.4 Interpretation	177
3.6 A Model of Carbonate Sedimentation for the Batu Raja Formation	178
3.6.1 Comparison with limestone outcrops	178
3.6.2 Development of the buildup and environments of deposition	183
(a) Restricted platform environment	183
(b) Open platform shallow subtidal environment	185
(c) Forereef slope	186
(d) Supratidal environment	188
 CHAPTER 4 DIAGENESIS OF THE BATU RAJA LIMESTONES	 189
4.1 Introduction	189
4.2 Micritisation	190
4.3 Bladed and Fibrous Cements	192
4.4 Dolomitisation	196
4.4.1 Introduction	196
4.4.2 Distribution of Dolomite	198
4.4.3 Determination of Dolomite Percentage and Relation to Insoluble Residue Content	203
4.4.4 Petrographic Characteristics of Dolomite	206

	(a) Dolomitisation of the micritic matrix	206
	(b) Replacement of calcite allochems	210
	(c) Replacement of evaporitic cement	213
4.4.5	Discussion	216
	(a) ZU Field	217
	(b) Duma Field	223
	(c) Nurbani Field	224
4.5	Alteration of Metastable Carbonate Mineralogies	226
4.6	Dissolution of Aragonite Allochems	229
4.7	Neomorphism of Micrite	232
4.8	Low-Mg Calcite Cementation	235
4.8.1	Syntaxial Overgrowths	236
4.8.2	Equant Non-ferroan and Ferroan Calcite Cements	237
	(a) Intergranular sites	239
	(b) Intragranular sites	239
	(c) Secondary porosity occluding cement	240
	(d) Fracture fill calcite	241
4.8.3	Displacive Calcite	241
4.9	Dissolution of Calcite	242
4.10	Silicification	243
4.10.1	Petrographic characteristics	243
4.10.2	Discussion	245

	<u>Page</u>
4.11 Pyritisation	248
4.12 Compaction	248
 CHAPTER 5 COMPARISON BETWEEN MODERN AND MIOCENE CARBONATES IN THE SOUTH-WEST JAVA SEA	 253
5.1 Pulau Seribu	253
5.1.1 Sediment Texture	253
5.1.2 Sediment Composition	258
5.1.3 Preservation potential of sediment characteristics	259
(a) Significance of bioturbation	260
(b) Chemical and physical instability of grain types	262
(c) Lithification of faecal pellets	263
(d) Absence of beach rock	264
5.2 Summary Depositional History of the Miocene Limestones	268
5.2.1 ZU Field	268
5.2.2 Duma Field	276
5.2.3 Nurbani Field	283
5.3 Summary of the Diagenetic Evolution in the Miocene Cores	290
5.3.1 Introduction	290
5.3.2 Early Diagenesis	292
5.3.3 Late Diagenesis	299
5.3.4 Discussion	301

5.4	Contracts Between Recent and Miocene Carbonates in the South-West Java Sea	301
5.4.1	Gross Morphology	302
5.4.2	Facies Comparisons	305

References	309
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Volume II

Plates

Appendices

LIST OF FIGURES

	<u>Page</u>
1. Index map of Indonesia showing study areas and major tectonic elements.	2
2. (a) Textural classification of Embry & Klován (1971). (b) Archie (1952) classification of porosity.	9
3. Map of the Pulau Seribu showing islands selected for detailed study.	13
4. Major structural elements, Northwest Java Basin, Mercator Projection (after Sujanto & Sumatri 1971).	15
5. (a) Annual reversal of winds and currents in the west Java Sea. (b) Annual distribution of rainfall.	17
6. Salinity and temperature distribution related to depth.	19
7. Typical cay-soil profile.	25
8. Characteristic biota and sediments of the reef flat.	32
9. Microenvironment created by burrowing <u>Callianassa</u> .	34
10. Morphology of permanently emergent and periodically emergent shingle ramparts.	40
11. Characteristic biota and sediments of the reef slope and adjacent environments.	42
12. Percentage of area covered by live and dead biota and unconsolidated sediment related to depth and exposure.	46
13. Profiles of the reef slope at Pulau Kotok Kecil.	48

	<u>Page</u>
14. Section through a bioeroded coral.	51
15. Recent reefs in North Sulawesi.	59
16. Map of the Sangkurang Archipelago, South Sulawesi.	62
17. Distribution of habitats on Pulau Pari.	66
18. Distribution of communities on Pulau Pari.	67
19. Distribution of lithofacies on Pulau Pari.	68
20. Characteristic grain size distributions related to environmental zones.	75
21. Triangular diagrams of Recent lithofacies of Pulau Seribu.	77
22. Changes in grain size profiles related to distance from reef base.	91
23. Percentage of insolubles in channel samples.	93
24. Hypothetical model of northern- and southern-type reef growth.	97b
25. Predicted shallowing-up sequence under conditions of continual gradual subsidence.	99b
26. The effect of eustatic fluctuations on reef growths.	100
27. Hypothetical model illustrating the coalescence of neighbouring reefs.	102
28. Relationship between northern- and southern-type reefs in the Pulau Seribu, and inferred subsidence of the Seribu Platform.	104

	<u>Page</u>
29. Classification of reef types (adapted from Maxwell 1968).	106b
30. Location of some Early Miocene reefal buildups in the southwest Java Sea.	111
31. Stratigraphy of the southwest Java Sea area (after Wight & Loos 1983, internal IIAPCO report, unpub.).	112
32. Location of wells and lateral correlation of units the ZU Field.	118
33. Location of wells and lateral correlation of units in the Duma Field.	119
34. Location of wells in the Nurbani Field.	120
35. Stratigraphy along the Rajamandala Ridge.	140
36. Palaeogeographic configuration of West Java during the Oligo-Miocene (after Martodjojo 1983).	141
37. Geological and location maps of the Bandung and Sukabumi areas.	142
38. Correlation of lithofacies along the Rajamandala Ridge.	152
39. Location map of the Sengkang Basinal Area.	155
40. Stratigraphy of the Sengkang Basinal Area (after Grainge & Davies 1983).	156
41. Location map of Cibinong Quarry, Parigi Formation.	172
42. Idealised lithofacies distribution in the Batu Raja.	180

	<u>Page</u>
43. Lateral correlation of lithofacies in the Nurbani Field (after Handoko 1983).	181
44. Percentage of dolomite and insoluble residues in the ZU Field.	199
45. Percentage of dolomite and insoluble residues in the Duma Field.	200
46. Percentage of dolomite and insoluble residues in the Nurbani Field.	201
47. Calculation of percentage dolomite from peak heights (after Tennant & Berger 1957).	204
48. Geochemical fan of the luminescence in dolomite and calcite (after Pierson 1981).	211
49. Determination of precipitational environment from cathodoluminescence (after Frank <u>et al.</u> 1982).	222
50. Characteristics of secondary mouldic pores in relation to matrix induration (based on Dodd 1966).	230
51. Relationship between pH and the solubility of calcite, quartz and amorphous silica (after Blatt <u>et al.</u> 1972).	247
52. Correlation of grain size parameters.	255
53. Summary logs of the ZU-4 and ZZZ-2 wells.	269
54. Summary log of the ZU-3 well.	270
55. Inferred evolution of the ZU Field.	272
56. Evolution of the ZU Field.	273

	<u>Page</u>
57. Summary log of the Duma-5 well.	277
58. Summary logs of the Duma-3 and Duma-9 wells.	278
59. Summary logs of the Duma-2 and Duma-11 wells.	279
60. Inferred evolution of the Duma Carbonate Buildup.	282
61. Summary logs of the Nurbani-3 and Nurbani-10 wells.	284
62. Summary log of the Nurbani-4 well.	285
63. Summary logs of the Nurbani-5 and Nurbani-6 wells.	286
64. Inferred evolution of the Nurbani Buildup.	289
65. Simplified diagenetic sequence of an idealised sample of Batu Raja Limestone.	293
66. Paragenetic sequence observed in the Batu Raja limestones (adapted from Robertson Research, Singapore).	294

LIST OF TABLES

1. Trends between grains size and component populations in the sand grade range.	70
2. Faunal composition of sediment in each environmental zone.	71
3. Characteristic grain size statistics of Recent lithofacies in the Pulau Seribu.	78
4. Mineralogy of faunal and floral groups (after Scholle 1978).	80

LIST OF PLATES

1. Physiographical zonation of a typical reef.
2. Islands selected for detailed study.
3. Variation in reef anatomy.
4. Features of cay marginal zones.
5. Sediment structures in the intertidal zone.
6. Features of mangrove mudflats and early colonisers of the cay.
7. Characteristics of coral growth and supratidal-intertidal zones.
8. Sand flat and algal zones.
9. Biota of algal zone and outer colonised moat.
10. Outer reef flat biota.
11. Lagoons and ramparts.
12. Characteristics and constituents of the shingle rampart.
13. Reef margin sediments
14. Shallow reef crest and slope communities.
15. Reef crest.
16. Reef slope biota.
17. Deep forereef environments.
18. Bored grains examined by SEM.
19. Borings and encrustations on Recent grains.

20. Microborings, encrustations and needle cement examined by SEM.
21. Blocky, needle and fibrous cements in Recent samples.
22. Beachrock.
23. Needle and rhombic Recent cements examined by SEM.
24. Microfauna from Recent unconsolidated reef flat samples.
25. Characteristics of northern and southern reefs in the Pulau Seribu.
26. Reef types illustrating hypothesised evolution of the Pulau Seribu.
27. Textures of the coral intraclastic floatstone-rudstone facies.
28. Textures of the coral intraclastic floatstone-rudstone facies.
29. Textures of the coral intraclastic floatstone-rudstone facies.
30. Textures of the foraminiferal-skeletal packstone-wackestone facies.
31. Textures of the algally bound floatstone facies.
32. Textures of the impure sandy grainstone facies.
33. Textures of the sparsely fossiliferous wackestone-lime mudstone facies.
34. Textures of the foraminiferal floatstone-rudstone facies and mottled floatstones.
35. Microtextures from the Batu Raja limestones.
36. Microtextures from the Batu Raja limestones.

37. Microtextures from the Rajamandala limestones.
38. Outcrops of the Rajamandala limestone.
39. Microtextures from the Sengkang Basin limestones.
40. Microtextures from the Sengkang Basin limestones.
41. Outcrops of the Parigi limestone and mounds in the Sengkang Basin.
42. Microtextures from the Parigi limestones.
43. Textures associated with micritisation.
44. Bladed and granular cements.
45. Neomorphosed early cements.
46. Fibrous cements.
47. Preferential dolomitisation^a of the matrix.
48. Textures of matrix micrite.
49. Porous and non-porous dolomitised intervals.
50. Dolomite textures under SEM.
51. Dolomite textures under SEM.
52. Authigenic clays in dolomitised intervals, under SEM.
53. Luminescent characteristics of dolomite crystals.
54. Dolomite lining and replacing allochems.
55. Dolomitisation of allochems.

56. Dolomite pseudomorphing selenite, and replacement of sparry calcite.
57. The occurrence and distribution of ferroan and nonferroan calcite.
58. The occurrence and distribution of ferroan and nonferroan calcite.
59. Mouldic solution porosity.
60. Neomorphic textures in allochems.
61. Selective dissolution textures.
62. Solution-infilling and micrite neomorphism.
63. Pore types and compactional textures visible in core slabs.
64. Cathodoluminescence characteristics of micrite and neomorphic spar.
65. Intraskkeletal porosity and matrix textures under SEM.
66. Inter- and intraskkeletal pore-filling calcite cement and syntaxial rims.
67. Cathodoluminescence characteristics of syntaxial rims.
68. SEM textures of calcite cement and microspar.
69. Calcite occluding primary and secondary porosity.
70. Sparry calcite under SEM.
71. Cathodoluminescence characteristics of sparry calcite cement and neomorphic spar.
72. Calcite cement textures and silicification.

73. Silicification textures.
74. Textures associated with pyrite growth.
75. Compactional features.
76. Fracturing, pressure solution and Talang Akar sediment.

LIST OF APPENDICES

	<u>Page</u>
1. Sample Location Map; Pulau Seribu	77
2. (a) List of Miocene Wells and Core Samples	78
(b) Localities of Miocene Outcrop Samples.	80
3. Key to Lithological Symbols used in the Carbonate Core Summary Chart ^s .	83
4. Carbonate Core Summary Chart ^s .	85 - 91

CHAPTER ONE

INTRODUCTION METHODS AND MATERIALS

1.1 INTRODUCTION AND OBJECTIVES

The primary aim of the thesis is an appraisal of Recent environments of carbonate sedimentation in the south-west Java Sea, Indonesia, and the proposal of a sedimentological model for the area, in order that this might assist in the interpretation of Miocene reefal buildups from the same area. The project developed as a result of the considerable importance of these buildups as hydrocarbon reservoirs (Leslie 1976; Beddoes 1980; Fletcher & Soeparjadi 1982). Because of the complex active tectonic regime in which the Miocene buildups developed (Fig. 1), and because of their relative isolation from the open ocean, it is difficult to draw close analogies between them and the classic areas of reef study such as the Great Barrier Reef, Bahama Bank and Florida Keys. The proximity between the Recent and Miocene sites of carbonate sedimentation studied however, and the similarity in their tectonic setting, invites comparison between the two.

The varying usage of terms such as ecologic, stratigraphic or organic reef, buildup, bioherm, biostrome and mound in the literature, has caused confusion and ambiguity (Dunham 1970; Braithwaite 1973). In this thesis, the term "reef" is used in the narrow sense of Lowenstam (1950) as refined by Braithwaite (1973). A reef has the following four qualifying attributes; wave resistance, a high proportion of frame builders, significant relief above the seafloor within the zone of wave action and finally, a zonation which is created and perpetuated by this self-generated relief. The term "carbonate buildup" is used to refer to a laterally restricted body formed of carbonate sediment which has topographic

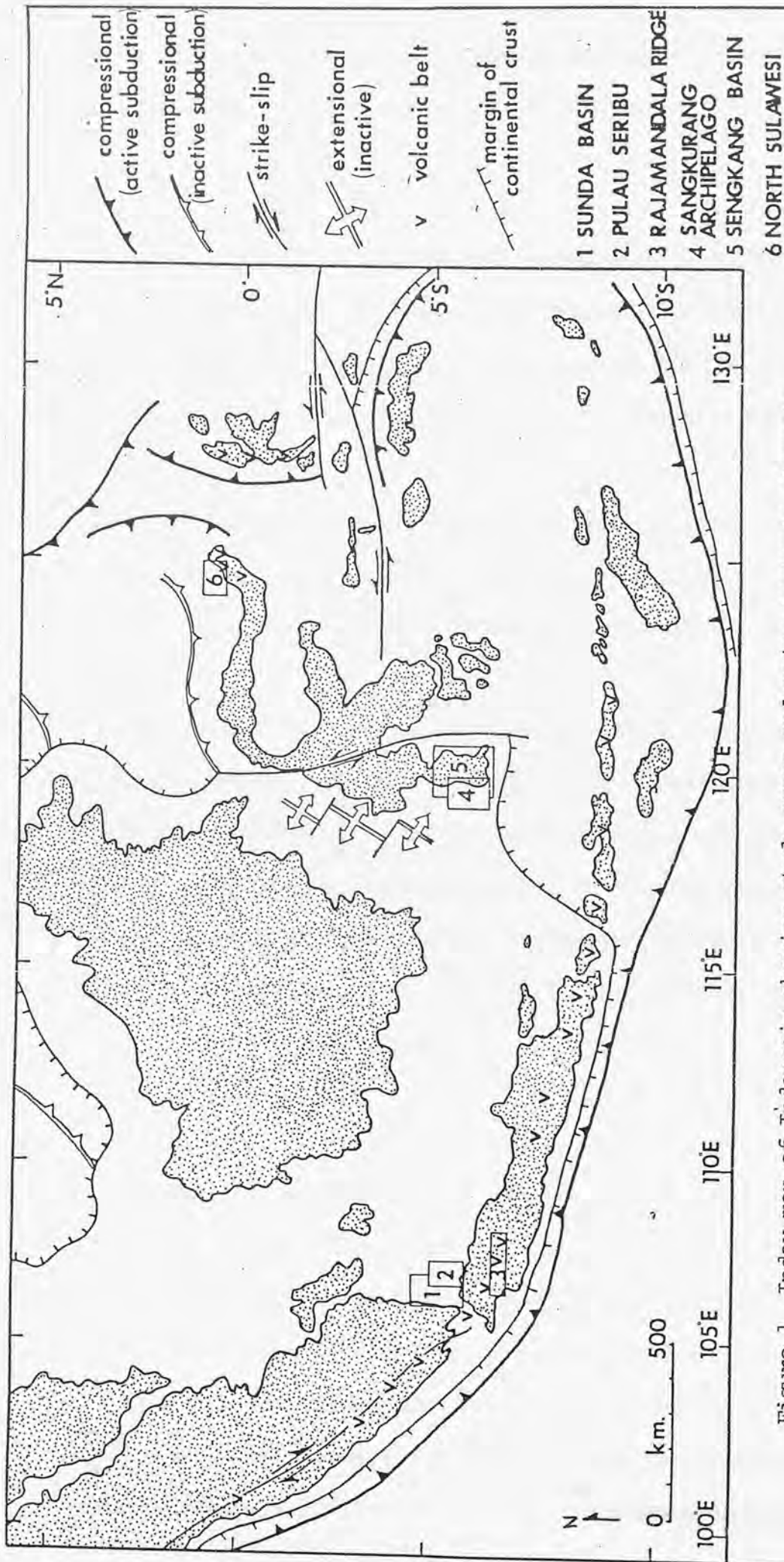


Figure 1 Index map of Indonesia showing study areas and major tectonic elements.

relief. Such a definition encompasses the reef as defined above, but buildup is used where insufficient framework is preserved to be sure that the structure was wave resistant.

In the study of Recent reefs, attention was focussed on the Pulau Seribu (Thousand Islands) reefs in the south-west Java Sea, although brief visits were also made to the Sankurang Archipelago in South Sulawesi and the reefs west of Manado in North Sulawesi. In assessing growth and development of Recent reefs, three main aspects are involved:

- (a) The identification of, and description of variation in, Recent sedimentary environments and the recognition of a number of distinct facies. The criteria by which facies are identified are discussed in Section 2.6.1.
- (b) Consideration of the evolutionary development of the Recent reefs through progressive stages to maturity. A three-dimensional model is presented illustrating the manner in which facies arrangement and geometry is modified from an incipient reef to a mature reef complex.
- (c) An appreciation of external controls on reef growth such as terrigenous sediment and tectonic control, and consideration of these influences on different types of Indonesian reefs.

Vertical and near-vertical cores from wells through the Lower Cibulaken Batu Raja Limestones (Early Miocene) were logged, and fieldwork was undertaken on the Rajamandala Limestones (Early Miocene) of west Java, Sengkang Basin Limestones (Eocene-Late Miocene) of South Sulawesi, and Parigi Limestones (Middle Miocene) of west Java. The characteristics and evolution of the Miocene Batu Raja buildups were also examined on a three-fold basis:

- (a) Study of important sediment-producing organisms and depositional facies based on visible characteristics from core logging and petrography. A

lithofacies stratigraphy of the buildups was established and facies sequences were used to infer the primary controls on carbonate deposition.

- (b) Study of diagenesis and the distribution of diagenetic products.
- (c) Study of the contrasts in the character of carbonate deposition between buildups developed in the Batu Raja Limestone and other fossilised Indonesian examples.

Chapter 1 covers general topics including sample collection and preparation. The remainder of the thesis is organised into three sections. Chapter 2 concentrates on Recent reefs and involves description and analysis of field data gathered from surface observations only. The three-dimensional model (Section 2.7) is inferential and involves ideas on the evolution of a single reef within the Pulau Seribu, and of the Pulau Seribu as a whole. Chapters 3-4 compare material from outcrops and subsurface Early Miocene buildups, and a picture is built up of the controls affecting Miocene sedimentation and subsequent diagenesis. Chapter 5 integrates the conclusions of Chapter 2 and Chapters 3-4 resulting in a comparison of Recent and Miocene sedimentary environments.

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1.3 RATIONALE BEHIND SITE-SELECTION IN THE PULAU SERIBU, AND COLLECTION OF RECENT SAMPLES

Selection of specific sites for investigation was carried out with the aid of aerial photographs and maps (Oceanographic chart 2056 1956, revisions 1980; Netherlands Government Survey charts, Thousand Islands Northern and Southern parts 1885-86). The sites were chosen so as to provide as representative an idea of the sedimentary environment as possible. Fieldwork was part boat-based and part island-based.

The patch reefs were systematically examined by snorkel and SCUBA diving to a depth of 35m. and sediment was collected from each identified sedimentary environment and subenvironment (Appendix 1). A sedimentary environment or subenvironment is a restricted area within which sediment is deposited under essentially the same conditions. 100-200 gm. of sediment were removed by hand and scooped into a polythene bag which was sealed underwater. The number of samples taken per unit was dependent upon the sediment area proportional that of the reef as a whole and variability within the sedimentary unit.

Underwater photographs were taken with a Nikonas III camera made

available by Robertson Research Limited, using Kodachrome 64 film.

Samples prefixed PSM, most of which are from deep inter-reef channels, were collected during 1983-84 by Mobil Oil as part of an independent Mobil Oil project. A remote grab sampler attached to a winch on board a boat was used to recover these samples.

1.4 SAMPLE TREATMENT

1.4.1 Recent Unconsolidated Samples

Two hundred unconsolidated sediment samples were collected from the Recent reefal environments. Sediment was stored wet in sealed plastic bags. After 12 hours drying at 40°C, approximately 100 gm. of sediment from each sample was separated, disaggregated by gentle crushing using a pestle and mortar, and sieved for 15 minutes on a Ro-Tap machine using a 0.5 ϕ interval. Class names proposed by Wentworth (1922) and the logarithmic grain size scale devised by Krumbein (1934) were adopted in calculation of the weight percents for gravel, sand and mud. Quantitative determination of the percentage frequency of various skeletal grains constituting samples from different environments was accomplished by point-counting. Four grain size fractions of each sample were selected, representing fine, medium, coarse and very coarse sand. Each fraction was impregnated with araldite resin, thin-sectioned and stained with combined stain (Dickson 1965) and from each section 500 points were counted. This was undertaken in order that compositional differences between different grain size groups were determined in addition to identifying variability between sample localities (Section 2.6.2).

The mud fraction of selected samples was examined by x-ray diffraction

to determine the mineralogy and hence infer probable genesis. The insoluble terrigenous fraction which, in most samples constituted a minor proportion of the total mud percent, was isolated by dissolving selected samples in 5% HCl and separately x-raying the residue.

1.4.2 Recent Coral and Mollusc Samples

Samples of both living and dead corals and molluscs were collected in order to study the variability and nature of bioerosion and cementation on the reef slope and reef flat. The samples were slabbed using a rotary saw, and examined with a hand lens. Selected samples were thin-sectioned for more detailed examination under a microscope.

1.5 SAMPLE TREATMENT; MIOCENE CORES AND OUTCROPS

SELECTION OF MATERIAL

Miocene samples from fourteen wells, and outcrop samples were used in the study. The wells came from three hydrocarbon reservoirs; the Duma, Nurbanic and Zu (=Bima) reservoirs from the south-west Java Sea. Work on the offshore reservoirs involved conventional logging of vertical and subvertical cores. Core logging and sampling was undertaken in the offices of IIAPCO and P. T. Lemigas in Jakarta.

The wells penetrate the entire Plio-Pleistocene, Upper, Middle and most of the Early Miocene. The cored interval varies from 9-75 m. and is restricted to the Batu Raja and Gumai formations. A list of core samples used is presented in Appendix 2. Conventional 12 cm. diameter slabbed cores were logged. Slabbing was done by P.T. Seta Yasa Ltd., Jakarta, Indonesia. Due to the nature and quality of the cored material from the Nurbani-10 and ZZZ-2 wells, these

cores were not slabbled and consequently difficulties were experienced in the subdivision of lithologies. Results are presented in the Carbonate Core Summary Charts in Appendix 4. The charts were devised based on a modified version of standard charts used by Robertson Research Int. Ltd.

The notation of sample numbers incorporates the field, well number and depth e.g. N41737' refers to a sample from the Nurbani-4 well from a depth of 1737 feet. Drilled depths are quoted in feet to preserve consistency with electric log charts and drilling depths used by the oil companies concerned and, except in the case of sample numbers, equivalent depth in metres is quoted in brackets. In Chapter 2, which concerns Recent carbonates, all distances are metric.

The lithological and palaeontological symbols used in this thesis are a blend of the Robertson Research standard legend and my own ideas (see Appendix 3 for explanation). The Embry & Klovan (1971, Fig. 2a) classification of limestone textures, and the Archie (1952, Fig. 2b) and Choquette & Pray (1970) classifications of porosity were adopted. Use of the Embry & Klovan classification permits a rapid and meaningful assessment of texture and relates well to environment of deposition. With a 1:180 vertical scale, lithologies less than 1' (30 cm.) thick are not represented in the lithology column. However, thin but significant bands are recorded in the comments section.

1.6 LABORATORY ANALYSIS

Facies analysis was carried out incorporating lithological relationships, field observations, results from core analysis, microfacies and diagenetic information from petrological studies. Rather than carry out a detailed palaeontological study, general palaeoecological observations were used to relate

Fig.2a TEXTURAL CLASSIFICATION OF EMBRY & KLOVAN 1971


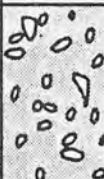







ALLOCHTHONOUS Original components not organically bound during deposition						AUTOCHTHONOUS Original components organically bound during deposition		
>10% components > 2mm				>10% grains 72mm		By organisms which act as baffles	By organisms which encrust and bind	By organisms which build a rigid framework
Mud supported		Matrix supported		Matrix Supported	Supported by 2mm components			
less than 10% grains	Greater than 10% grains		No lime mud					
MUD ~STONE	WACKE ~STONE	PACK ~STONE	GRAIN ~STONE	FLOAT ~STONE	RUD ~STONE	BAFFLE ~STONE	BIND ~STONE	FRAME ~STONE
								

Fig.2b

ARCHIE CLASSIFICATION OF POROSITY (1952)
(Modified by Robertson Research Singapore Ltd)

Type	I II III	compact, crystalline chalky, dull, earthy granular	appearance in hand specimen
Class	A B C D	none visible, <20μ 20—125μm 125μm-2mm >2mm	visible pore size
Interconnection	c d	connected pores disconnected pores	
Crystal Size	very fine fine medium coarse	50μm 100μm 200μm 400μm	
Description	good fair poor absent fractures only	<div> <div></div> >10 <div></div> 5-10 <div></div> <5 <div></div> No pores visible <div>F</div> </div>	% of surface covered by visible pores

organic associations and sedimentary features. A systematic laboratory programme was undertaken involving the following techniques:

1.6.1 Peels

The technique followed is that described by Stewart & Taylor (1965). Peels were examined under a microscope after being mounted between glass slides. The acetate peel was also used as a negative so that photographic enlargements of structures could be taken.

1.6.2 Thin Sections

Samples collected for thin-sectioning were representative of specific limestone facies or textures. In staining of sections and peels, the technique described by Dickson (1965) was adopted. Combined stain was used to facilitate the differentiation of carbonate minerals through qualitative colour comparison, and recognition of different iron compositions. Petrographic description follows the nomenclature of Friedman (1965a).

A series of photomicrographs were taken using a Zeiss Photomicroscope II. The photographs illustrate characteristics of particular facies and specific diagenetic fabrics referred to in the text.

1.6.3 X-ray Diffraction

Selected samples of Miocene and Recent material were x-rayed using Ni-filtered CoK α radiation on a Phillips PW 1130/40 machine. Diffractograms were analysed to determine constituents of the clay mineral assemblages, and the calcite: dolomite ratio calculated using peak heights (Section 4.4.3).

1.6.4 Cathodoluminescence

Uncovered and unstained thin sections were examined by a Technosyn Cold cathode luminescence model MK11, using a 500 mA gun current and a kV between 12 and 15. The thin sections were highly polished and cleaned with inhibisol prior to examination.

The interpretation of luminescence in the rocks studied uses the conclusions derived from the work of a number of previous workers. Stehli & Hower (1961) and Veizer (1983) gave predictions of Mn^{2+} for marine dolomites. The amount of Mn in dolomite has been correlated with the openness of the diagenetic system and intensity of alteration (Brand & Veizer 1980; Veizer 1983).

1.6.5 Scanning Electron Microscopy

Scanning electron microscopy (SEM) was used to examine details of limestone and unconsolidated sand constituents, the character of lithified lime mud and the textures of calcite cement, neomorphic spar and dolomite. The instrument used was a Cam Stereoscan 150 model. Washed sand grains from Recent unconsolidated samples and fresh fracture surfaces of Miocene samples were gold-coated in order to produce good electrical conductivity and reflectance of the electron beam. The surface to be examined was 5-10 mm. in maximum dimension and was chosen where possible exhibiting moderately homogeneous characteristics representative of the feature of interest. This minimises uncertainties introduced by the presence of multiple diagenetic textures.

CHAPTER TWO

PULAU SERIBU

2.1 INTRODUCTION AND PREVIOUS WORK

There are an estimated 15,000 to 16,000 fringing and barrier reef systems in Indonesia (de Neve 1981), together with more than 800 coral islands which occur mainly in the eastern part of the Indonesian Archipelago. A group of patch reefs in the south-west Java Sea was investigated as part of this study (Fig. 3). The Pulau Seribu (=Duizeng Islands of van Bemmelen 1949) are situated between latitudes $5^{\circ}25'$ - $5^{\circ}57'S$ and longitudes $106^{\circ}30'$ - $106^{\circ}40'E$, and the reefs grow on a shallow platform 30-40 m deep (Fig. 3). In this study, particular emphasis was placed on the controls on the loci of carbonate deposition, facies distribution and the predicted subsequent diagenesis and porosity evolution.

During the inter-war period, geological and biological studies in reef physiography and coral growth were conducted in the Bay of Batavia, since renamed Jakarta Bay, by several Dutch workers including Umbgrove (1928, 1930, 1939) and Verwey (1931). The Dutch-Indonesian Snellius expedition undertook a scientific programme in the south Java Sea, offshore South Sulawesi and in the Timor Arc. This work resulted in the publication of geological and biological descriptions (Kuenen 1933). During the post-war period carbonate sedimentological studies were conducted in the Pulau Seribu by Umbgrove (1947) and van Bemmelen (1949). Over the last decade, Recent environments of carbonate sedimentation in Indonesia have become the focus of study of petroleum geologists, in order to facilitate the interpretation of ancient carbonate buildups (Scrutton 1976, 1979).

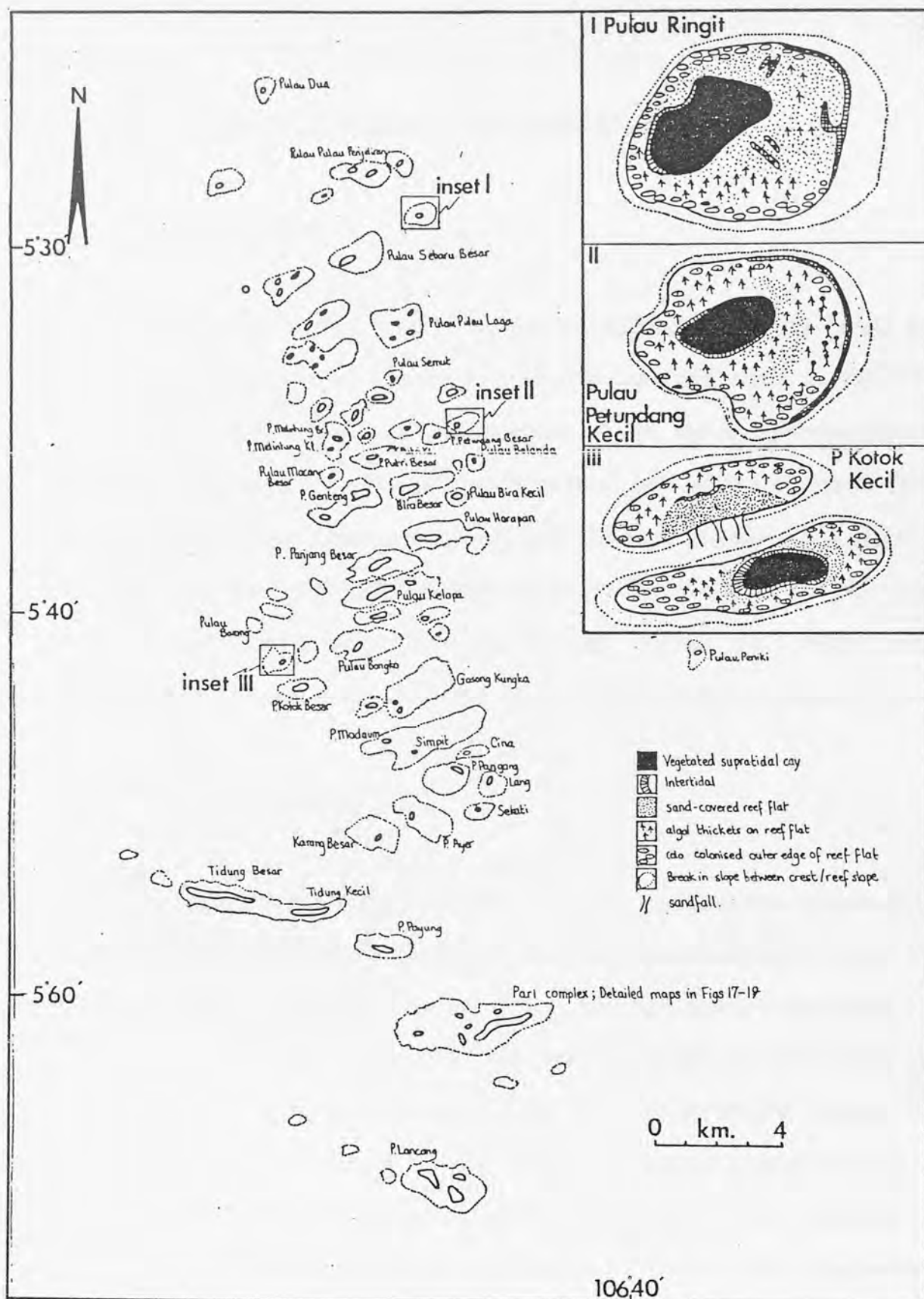


Figure 3 Map of the Pulau Seribu showing islands selected for detailed study.

2.2 GEOGRAPHIC, TECTONIC AND CLIMATIC SETTING

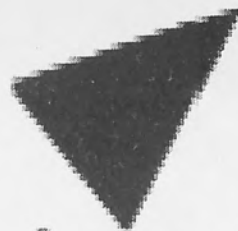
2.2.1 Regional Setting

The Pulau Seribu are located on the Seribu Platform in the Sunda Shelf Sea. The Sunda Shelf is the most extensive coherent shelf in the world, comprising the Gulf of Thailand, the Malaccar Straits, the south-western part of the South China Sea, Java Sea and south-western part of the Macassar Straits (van Bemmelen 1949). Contemporaneous with the Post-Pleistocene eustatic sea level rise there was epeirogenic subsidence of the Sunda shelf. Thus the Pulau Seribu may represent a better analogue to many ancient reefs which grew in epeiric seas, than those areas of modern reef study which lie on ocean margins.

2.2.2 Tectonics and Basement

The Seribu Platform is a submerged low relief plateau trending NNE-SSW for 40 km. from the coast north-west of Jakarta. The Platform is 12 km. wide and fault-bounded; to the east by the Arjuna Sub-basin and to the west by the Sunda Trough. The area within which the reefs are growing is one of the most tectonically active belts in the world (Fig. 4). The structural framework is discussed by Ben-Avraham & Emery (1973). Vertical movements of the substratum have been strong and relatively swift and this has affected reef development by influencing sea level fluctuations and relative land subsidence.

The southern part of the Platform is segmented by a submerged pre-Pleistocene drainage system. East-west orientated gorges were identified by van Bemmelen (1949). The rivers which cut these valleys deposited coarse clastic sediments which are overlain along the Java Sea margins by clayey fluvial sediments of the larger Sunda islands. The Pulau Seribu have grown up since the



Aston University

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FIGURE 4. MAJOR STRUCTURAL
ELEMENTS, JAVA SEA AREA.
a. Sujanto & Sumatri 1977
Mercator Projection.

post-glacial sealevel rise and are therefore very young compared with other major areas of reef development such as the Great Barrier Reef (Davies 1983) and Bahaman-Florida Platform (Bathurst 1975).

The substrate in which the Pulau Seribu are rooted is unknown. With the flooding of the Platform during the post-glacial sealevel rise, sites of reef growth are likely to have been controlled by minor topographic elevations. In view of the presence of the Pleistocene drainage system, such features as fluvial levee deposits may have provided a substrate for reef initiation (Section 2.7.4). Reef growth is not continuous to the edges of the Platform although the reasons for this are unclear.

2.2.3 Climate

Since Indonesia straddles the equator, environmental conditions fluctuate very little annually, compared with the subtropical reefal areas of Australia and the Caribbean. The biannual reversal of winds and currents governed by the monsoonal climate (Fig. 5a), is instrumental in reef construction and shape (Umbgrove 1930). The alternating monsoon controls both reef growth and post-mortem redistribution of debris causing many of the Pulau Seribu islands to be elongated east-west (Plates 1, 2a, 3c, 25), orthogonal to the long axis of the underlying platform. Since neither reef flank is constantly in the lee of, or exposed to, the prevalent winds and currents, pronounced low energy and high energy rims are not formed.

Mean annual air temperature at sealevel is slightly above 26°C and mean humidity measured on the Java coast is 80%. The average annual precipitation of greater than 2 m. is seasonally distributed (Fig. 5b) concentrated in the east monsoon. Rains tend to be of short duration and torrential intensity.

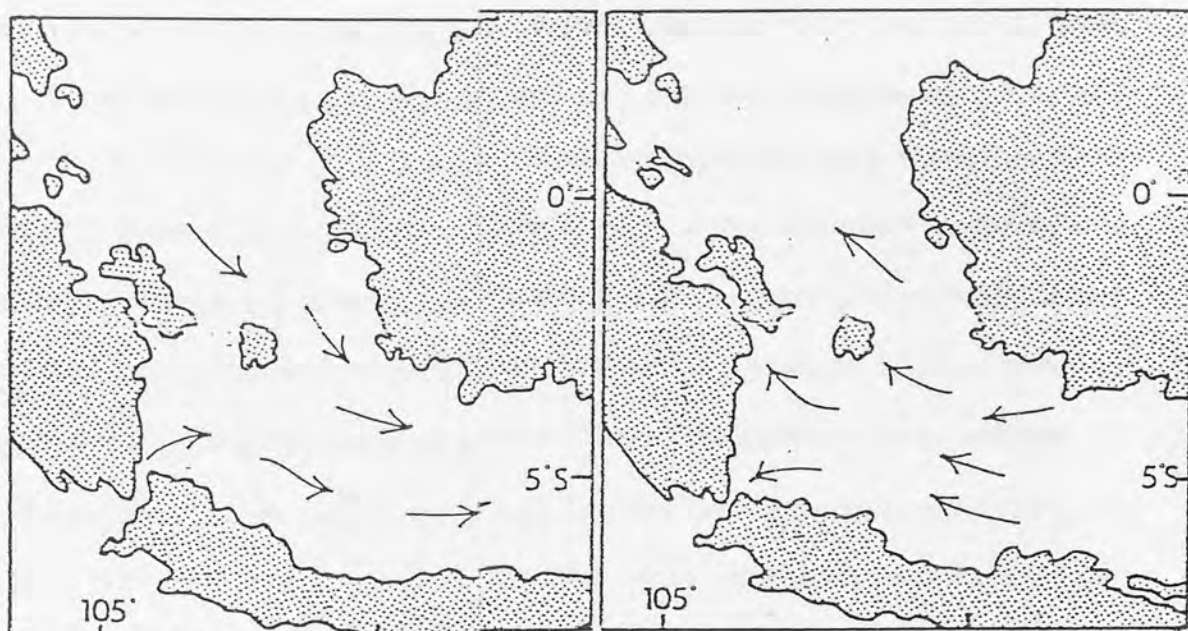


Figure 5 (a) Annual reversal of winds and currents in the West Java Sea^a

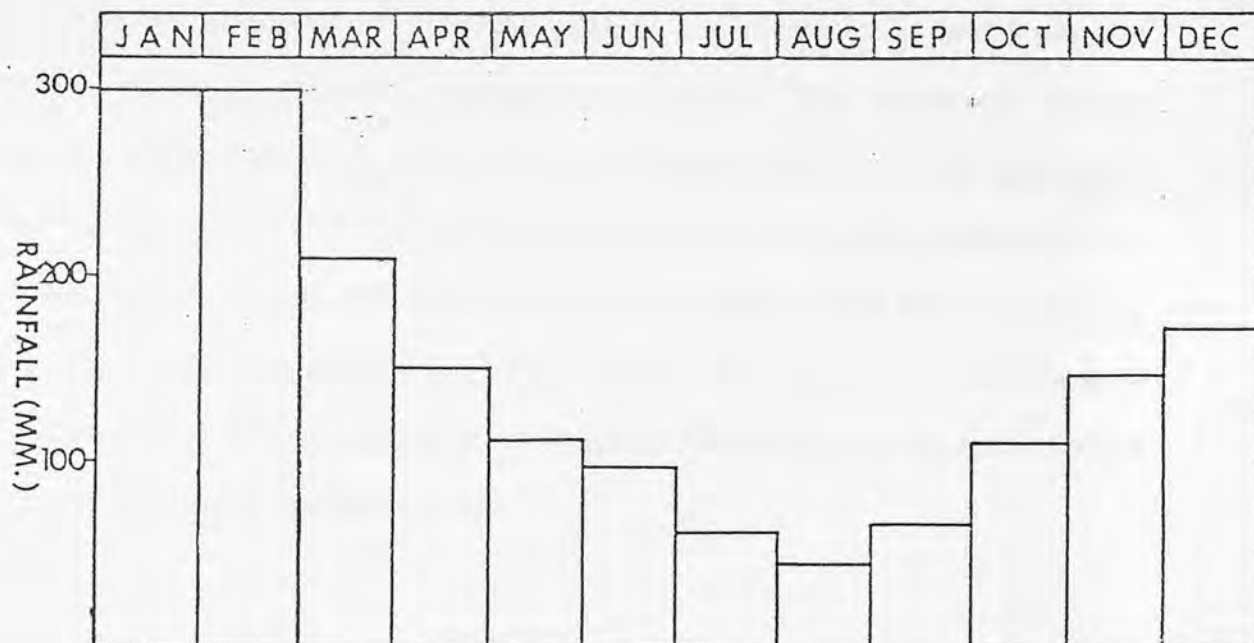


Figure 5 (b) Annual distribution of rainfall. Data from World Weather Guide 1984. Figures averaged over a 30 year period.

Surface water temperature averages 28.5°C dropping to 27.5°C at a depth of 3 m. and 26.5°C at 15 m. (Fig. 6, personal data combined with data from L.O.N.). Temperature peaks at the surface at 3 pm, but at depths of 2-4 m. the maximum is not attained until 6 pm. Minimum temperatures throughout the water column occur at 3 am. At depths exceeding 2 m., minimum temperatures are maintained for longer periods and maximums for shorter periods than at the surface. The yearly lowest temperatures throughout the water column occur in January, and the annual maximum at greater than 4 m. depth in June, between 1-3 m. in July and at the surface in October. Diurnal temperature fluctuations are greater in the east monsoon than in the west monsoon, although these fluctuations are only significant in the shallow areas of reef flats where temperatures reach 38°C .

Salinity ranges between 29-33.5‰, diurnal and annual fluctuations being greatest at the surface (Fig. 6). Diurnal variation in salinity approximately mimics the fluctuations in temperature, peaking between midday and 3 pm and reaching a minimum between midnight and 3 am. The maximum diurnal fluctuations occur during the east monsoon. Reef flat area is small enough to prevent the development of hypersaline or stale back-reef water masses such as have been described from the Bahamas (Bathurst 1975 p.101) and Florida Bay (Taft & Harbaugh 1964 in Bathurst 1975 p.149). The area is microtidal and is characterised by diurnal cyclicity in contrast to the more normal semi-diurnal tides of the Atlantic and Indian Oceans.

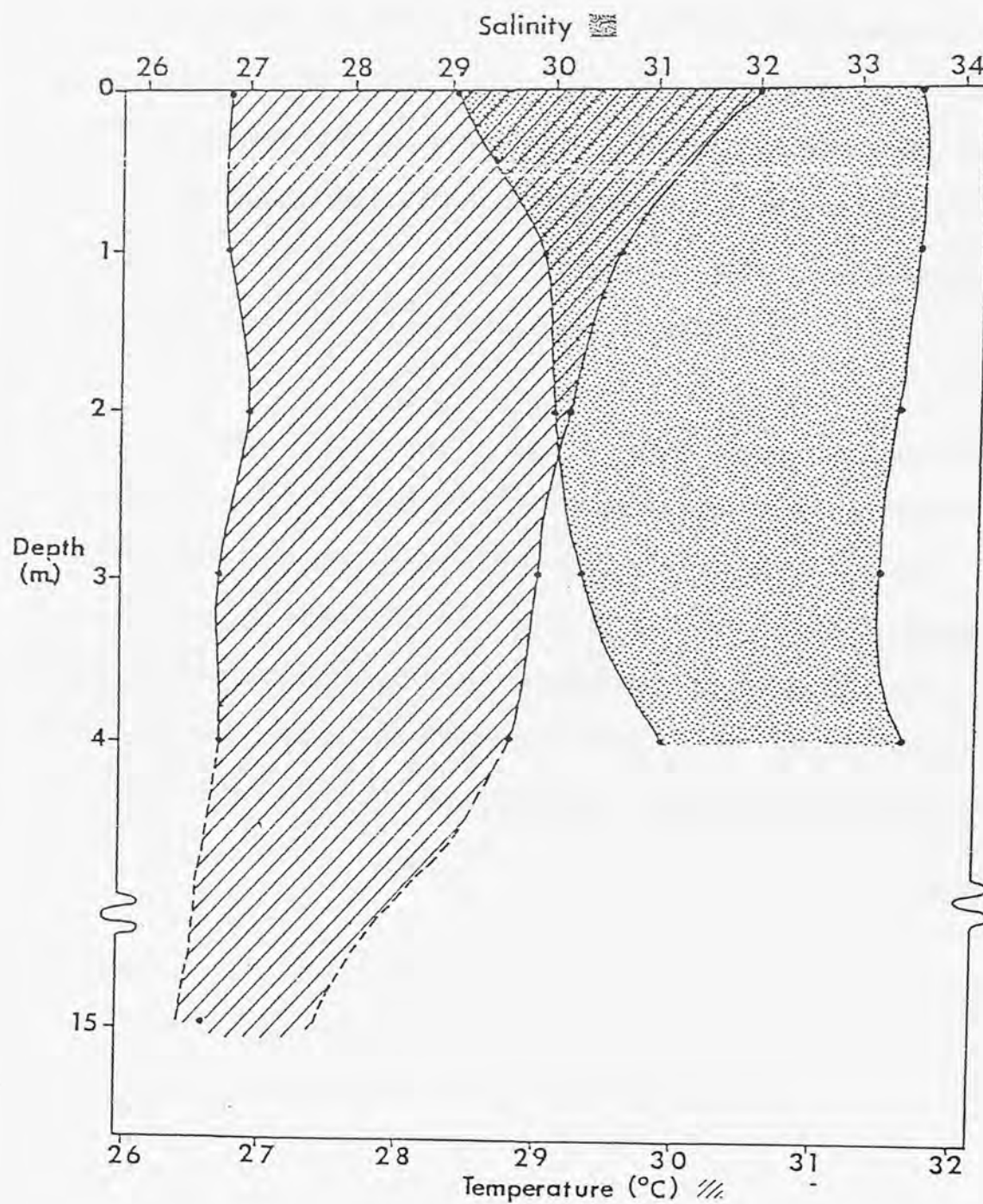


Figure 6 Salinity and temperature distribution related to depth.

2.3 REEF ANATOMY

The Pulau Seribu reefs are spaced from 35 m. to 6 km. apart and average spacing decreases northwards. Individual reefs range from 50 m. to 3 km. in maximum dimension, and ratio of reef length to width varies between one and twelve, also decreasing northwards. The reefs grow upto sealevel as they mature, and are separated from each other by channels most of which are 30-40 m. deep. The 4.8 km. wide east-west orientated Outer Channel in the southern part of the Pulau Seribu is 68 m. deep in the deepest part, and represents part of the palaeodrainage system referred to in Section 2.2.2.

The Pulau Seribu reefs exhibit a high degree of consistency in physiography and seven horizontal and vertical zones can be recognised (Plate 1). Identification of separate zones and subzones was made on the basis of water depth or elevation above sealevel, ratio of percentage in situ substrate to percentage unconsolidated sediment, the nature and diversity of faunal and floral associations, wave energy and sediment texture. Terms used to describe zones purposefully avoid direct genetic implications and are based on environmental characteristics.

Most of the islands consist of a vegetated cay surrounded by a reef flat, frequently partly enclosed within a periodically emergent coral shingle bank which borders the reef drop-off. Reefal zones identified are;

- (i) sand cay
- (ii) reef flat
 - (a) algal flat
 - (b) sand flat
 - (c) outer colonised moat
- (iii) lagoon

- (iv) shingle rampart
- (v) reef slope (a) crestal zone
 (b) reef wall
- (vi) reef base
- (vii) channel.

These are discussed in Sections 2.3.1 - 2.3.7 and the associated lithofacies in Section 2.6.

Four islands; Pulau Pari, Pulau Kotok Kecil, Pulau Petundang Kecil and Pulau Ringit, exhibiting contrasts in size, complexity and geographical position, were selected for detailed study. Sediment sampling and identification and description of reefal zones were primarily undertaken on these islands (Fig. 3I-III) although a large number of other patch reefs throughout the Pulau Seribu were also visited and sampled in lesser detail.

(a) Pulau Pari

The Pulau Pari complex is 3 km. long and 2 km. wide and is the largest patch reef in the Pulau Seribu. It comprises a complex of lagoons and cays (Plate 2a) and is located at the southern end of the Pulau Seribu chain, north of the Outer Channel. A long shingle rampart is developed on the northern and eastern rims of the reef. The northern reef slope is exposed to the strongest wave action and is shallower than the southern slope which is exposed to relatively stronger currents. The contrast in coral assemblages resulting from the contrasting hydrodynamic regimes is discussed in Brown et al. (1982).

Pari is also the name of the largest cay which is approximately 1 km. long and is located on the eastern end of the complex. This island supports mature vegetation, and a mangrove flat is developed to the north-west. The smaller

islands; Tengah, Kongsu, Burung and Tikus, located on the western half of the complex, are probably considerably younger and support a more shrubby colonising type of vegetation. The lagoonal complex comprises two connected lagoons around which mangroves and new cays are establishing themselves.

(b) Pulau Kotok Kecil

Pulau Kotok Kecil, comprising two closely spaced reefs is located on the western side of the Pulau Seribu chain (Fig. 3c, Plate 2d) and is exposed to the western monsoonal storms between April and November. A vegetated cay is developed on the southern reef and to the north, the submergent patch reef supports a small periodically emergent mobile sand cay. Between the reefs is a shallow channel, 18 m. deep, through which flow strong currents upto 31 cm.s^{-1} . Sand falls on the southern slope of the northern reef supply sediment to this channel. The reef flat is upto 20 m. wide and unlike the Pulau Pari complex, there are no sheltered areas on the reef flat.

Vigorous coral and Halimeda growth occurs on the north-west side of the reef an less vigorous growth on the southern side of the southern reef. Coral growth is slow and patchy in the shallow inter-reef channel.

(c) Pulau Petundang Kecil

Pulau Petundang Kecil is situated on the eastern side of the Pulau Seribu chain (Fig. 3b, Plate 2c), and is exposed to the full force of the eastern monsoon, (November - March). A large rampart is developed on the eastern margin and a vegetated cay is sited asymmetrically on the western leeward side of the patch reef. Mangroves have developed on shingle bars on the outer western reef flat. A rich Halimeda zone is developed seaward of the rampart on the eastern rim of

the reef. The eastern crest is wider than on most reefs, and absorbs the considerable energy of shoaling waves. Coral growth is vigorous right around the reef.

(d) Pulau Ringit

Pulau Ringit (Fig. 3a) is in the extreme north of the Pulau Seribu, totally isolated from any Java-derived freshwater contamination and beyond the limit of penetration of most weekend diving and tourist groups. The patch reef is relatively sheltered from weather by surrounding islands. In this northern extremity of the Pulau Seribu, the east-west elongation of islands and cays is less pronounced. Ringit cay itself is equant in plan. Pulau Ringit has a rampart which is emerged only at extreme low tide. The crestal zone to the north-east of the cay is considerably wider than on other flanks, in response to preferential coral growth in the most exposed location.

2.3.1 Sand Cay

(a) General Characteristics

Emergent sand cays occur on most reefs and are generally elliptical or arcuate in plan, ranging in length from 50 - 3000 m., and in width from 30 - 150 m. The initial locus of sand accumulation on the reef flat represents the focal point of waves refracting on the reef edge. Cays in the south of the Pulau Seribu group tend to be smaller relative to the reef area compared with those in the north (Plate 2b, 3a & b, 11f), although the southern cays are larger in absolute terms. Relief is very low attaining a maximum of approximately 2 m. above sealevel.

In the early stages of development, the cay is unstabilised and consists of a mobile sand wave which is reworked periodically by storm activity with resultant radical changes in shape. Such sand bodies are commonly flooded at high tide e.g. Pulau Kotok Kecil, Gosong Bira (Plate 2d). Such bodies build very rapidly once established although permanent survival depends on their attaining increased stability through floral colonisation (Plate 6d). Between December 1983 and June 1984 the intertidal sandbank on the submerged northern reef of Pulau Kotok Kecil grew from a 10 m. long arcuate bank to a 25 m. long undulose ribbon-shaped body. Most cays are permanently emergent and stabilised by the growth of such vegetation as coconut trees and shrubs. The continued growth of the cays is evidenced by the development of intertidal spits at the eastern and western ends of cays, offshore bars and the encroachment of mangroves onto the reef flat (Plate 7c).

The Pulau Seribu exhibits five types of cay which, in order of increasing maturity are;

Type I submerged sand bar emergent only at low tide, e.g. reef immediately north of Pulau Kotok Kecil; Plate 2d, 25d.

Type II low lying sand or shingle cay, e.g. Pulau Barang.

Type III lying cay with pioneer strandline plant community, e.g. Pulau Belanda.

Type IV higher standing cay with more complex better developed vegetation including trees, e.g. Pulau Putri Besar.

Type V sand cays with mangrove growth and sometimes mangrove swamps, e.g. Pulau Pari.

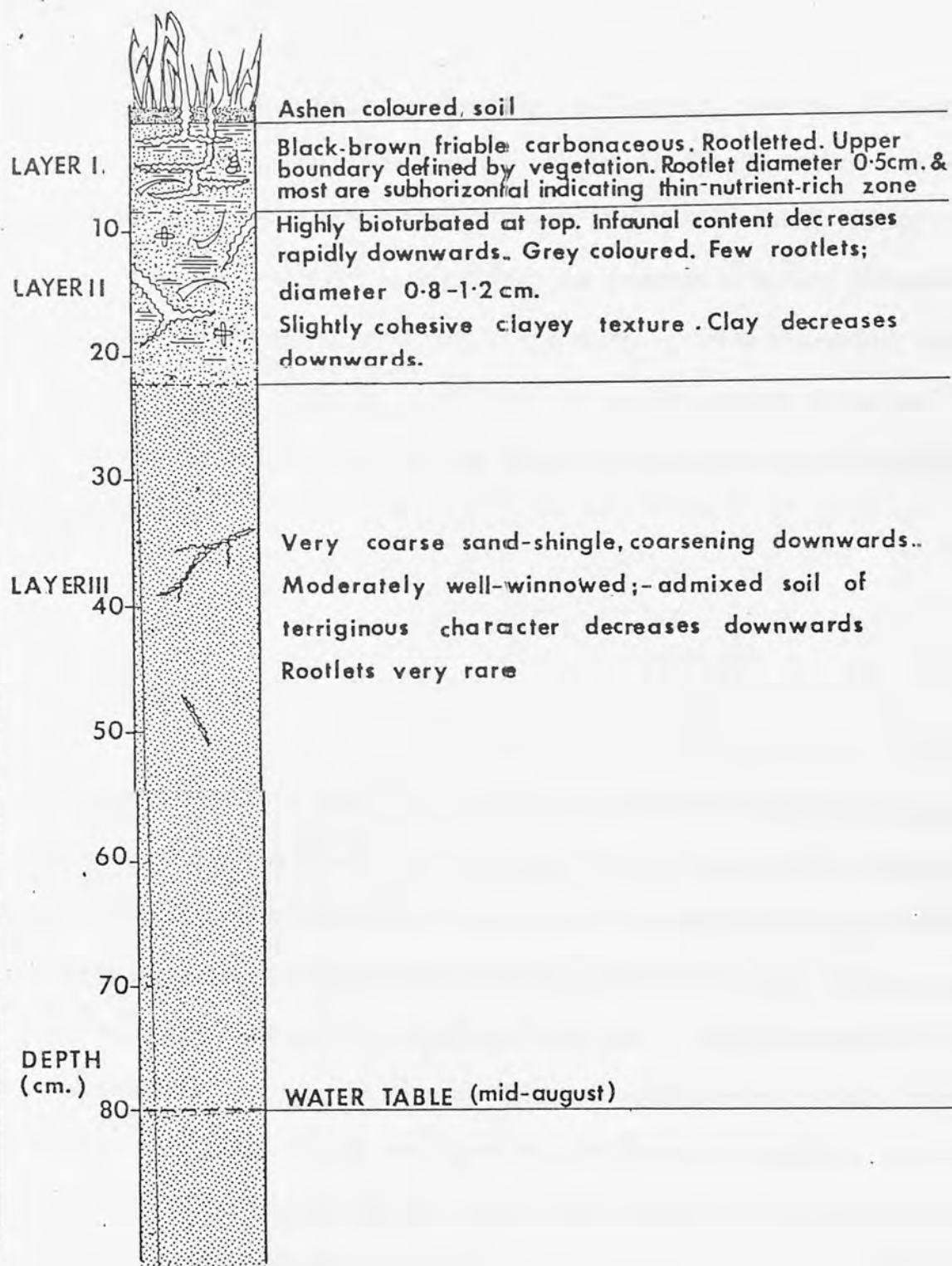


Figure 7 Typical cay-soil profile.

A number of soil pits approximately 1 m² in plan, were dug in the cay substrate and three soil layers were identified (Fig. 7). On the smaller cays (e.g. Pulau Kotok Kecil, Pulau Macan Kecil) the soil profile is immature and layers 2 and 3 are very thin. This is associated with the presence of a more pioneering-type of vegetation compared with that in the south. A fresh to brackish water lens is present on the vegetated islands and depth to the water table varies from 0.4 - 0.8 m. Sediments from the cay belong in the carbonaceous lithofacies (Section 2.6.3f).

(b) Intertidal Subzone

The margins of the cay are gently shelving intertidal beaches, mangrove clumps or mudflats (Plate 4-6). Intertidal sand flats can be very wide such as on Pulau Pari where 500 m. of sand is exposed intertidally during spring lows (Plate 5a). Bars of intertidally exposed sand prograde onto the reef flat. The beaches are sediment sinks and occur on the convex windward or exposed margins. They are ribbon-like in plan, 3 - 15 m. wide and trend approximately parallel to the reef edge. A pit dug through the intertidal sand revealed complete oxidation down to the water table. The well-sorted coarse sand is slightly aligned but exhibits no inclined bedding lamination or distinct burrows. This is attributed to pervasive bioturbation by crabs and shrimps.

In 1983, an attempt was made to drill through the intertidal zone using a hand-operated hydradrill. Although recovery was negligible due to the largely unconsolidated nature of the material, the exercise provided an idea of the depth of unconsolidated sand and the subsurface stratification. In the top 6 m., six indurated layers upto 8 cm. in thickness occurred, and between 6 - 11 m. depth numerous thin hard streaks were detected. These results are similar to the description of the first Funafuti reef boring in 1897 (Rodgers 1980) reported to have encountered cavernous core rock at 40-50' (13-16 m.) but otherwise just very loose organic sand.

Beaches slope gently seaward in a series of step-like wave-built berms or cusate sand ramparts concave to the island. The texture is variable from coarse well-sorted sand in the lower intertidal zone to poorly-sorted shingle in the upper intertidal zone (Plate 4b). Coral fragments upto 50 cm. long are washed up on the beach. The fine burrowed intertidal sands are commonly pelleted on the southern shores of Pulau Pari (Plate 4c).

Beach sands belong in the winnowed coral-mollusc grainstone lithofacies (Section 2.6.3e). Sand-sized grains are moderately to highly rounded and abraded whilst the shingle fraction comprises subangular broken corals and broken or whole molluscs. Beaches are bound on the landward margin by a colonised bank which edges the elevated central portion of the cay (Plate 4a). A strandline of dead vegetation and scattered coarse skeletal fragments defines the uppermost intertidal limit. On sheltered margins this interfingers and grades in with the rooted vegetation, sometimes with a step of between 20 - 100 cm., for example on Pulau Pari.

The lower intertidal zone in sheltered areas is pock-marked with trails and tracks of the gastropod Cerithium, and of the echinoid Marthasterias glacialis (Plate 4d). Commonly a very thin mucilaginous algal film of negligible cohesiveness forms a brownish scum on the sediment surface. A similar subtidal gelatinous film, though of rather greater cohesiveness, described by Bathurst (1967) was found to contain a large proportion of blue-green algae. On relatively exposed margins such as the eastern margin of Pulau Kotok Kecil and western margin of Pulau Ringit, the beach undercuts the vegetated cay and a soil profile is exposed in an 80 cm. undercut ledge. At such localities, the beach is generally slightly steeper and narrower and characterised by a molluscan assemblage resembling that of the agitated reef flat and notably devoid of the gastropod Cerithium. A slightly more robust "tufted" filamentous algal layer is present rarely on such agitated intertidal shores. These films are only preserved for any length of time where they remain permanently beneath a thin film of water and therefore, where found, are a good indicator of marine phreatic conditions.

The lower limit of the beach is the low tide limit. The lower intertidal sands are commonly rippled in the ripple-swash zone (Plate 5c). Ripples are perpendicular to the wind direction and have a wavelength of approximately 0.5 metres and an amplitude of 1-2 cm. A pit dug in the lower intertidal sands at Pulau Pari revealed an anoxic layer (Plate 5b) from just below the surface to a depth of 8 cm. which is attributed to decay of organic matter. Below this layer the sands are again oxidised. The contact between oxidised and unoxidised layers is undulose and slightly burrowed. No bedding lamination is present. Conical

burrows of the decapod Callianassa (Shinn 1968a; Plate 13b) are encountered within the intertidal zone of large reefs such as Pulau Pari and Pulau Ayer. Only where there is a sufficient depth of unconsolidated sand to accommodate these infauna. The tops of the Callianassa burrows are planed off by the falling tide (Plate 5d) but preserve an open exhalent hole. In troughs between the burrowed areas, tolerant species of Thalassia colonise. The troughs, which remain flooded except during exceptionally low tides, and the exposed sand spits, interdigitate. Sand spits prograde onto the reef flat in the lee of shingle bars or small new cays, thus the transition between intertidal and reef flat zones is gradational and consequently interlayering of the sediment is predicted in a vertical sequence.

Low energy margins of some cays, generally north-west facing concave rims, are characterised by development of intertidal mangrove mud flats (Plate 7c). These are found only on the large reefs where wide shallow bays such as that to the north-west of Pulau Pari, are isolated from the wind and wave energy on the outer reef edge. Mangrove roots help to baffle water movement and further dissipate hydrodynamic energy (Plate 6a). Sediments are fine dark oozy muds high in organic content (Plate 6c). The upper intertidal boundary here is also marked by a stable vegetated bank 0.5 - 1 m. high. The mud flats have very low relief, varying in width from 3 - 15 m., and the reefward boundary is gradational into the subtidal reef flat. The main member of the faunal and floral community is the mangrove Avicennia which grows either scattered or in dense thickets. Infaunal diversity is low and limited to scattered annelids, Callianassa and stonefish.

The mangrove muds are unbedded, lack lamination, and contain abundant mangrove rootlets. The surface of the mud is speckled with small gas holes 0.5 - 1 cm. in diameter (Plate 6b), and spaced approximately 6 cm. apart. The muds are commonly pelleted and patchily covered by a thin non-cohesive film of rusty-

coloured cyanophytic algae. Rare Callianassa burrows bring up medium to coarse grained sand to the surface. A trench dug in the muds reveals thoroughly homogenised sediment to 60cm. and below the surface the muds become anoxic and smell strongly of hydrogen sulphide.

Scattered mangroves do occur in exposed sites on reef flats for example at Pulau Petundang Kecil (Plate 7a), and so the presence of mangroves or mangrove rootlets in a cored section need not be indicative of a very sheltered environmental niche.

2.3.2 Reef Flat

The reef flat is a shallow carbonate platform which constitutes the greatest percentage of the total reef area. It is generally elliptical in shape, 15 - 30 m. wide and bordered seawards by the reef slope. The cay, where present, is asymmetrically located on the reef flat, generally on the western half (Plate 7b).

The reef flat slopes gently seaward from the intertidal subzone to a marginal 'moat' (Brown et al. 1982) 1 m. deep just inside the reef edge. Waves impinging on the reef edge encounter considerable frictional resistance due to the shallowness, and water energy is rapidly dissipated. Roberts (1980) using wave height changes, calculated that energy loss at the reef crest ranges from 70 - 90 %. Coral and algal growth on the reef flat occurs in a well-defined radial pattern (Plate 7a) which may result from channelised centrifugal draining of stale waters from the reef flat at low tide.

Sedimentary structures are varied and mainly of small scale. Lamination is absent but rippling is common on the windward shallow inner part of the reef flat especially on the extreme eastern and western edges of islands.

Symmetrical ripples with long axes orientated at a shallow angle to the reef edge, form in mobile uncolonised sand substrates, particularly at high tide when wave energy is less diminished by shingle ramparts. The amplitude of the structures is 1-2 cm. and wavelength approximately 6 cm. Current ripples are absent since directional currents are negligible inside the reef edge.

The reef flat comprises a number of subenvironments;

algal flat

sand flat

outer colonised moat.

(a) Algal Flat

The algal flat occurs on parts of the reef flat which are permanently submerged at a depth of 0.3 - 0.8 m. The community is composed of a mixed algal assemblage, the most common members of which are Thalassia, Padina, Sargassum, Zostera, Caulerpa and Halimeda. Areas of colonisation are elliptical or irregular in plan. Thalassia is a particularly prolific coloniser of low energy inner reef flats (e.g. north-west Pulau Pari). There the substrate is isolated from current and wave activity and the reef flat is protected in the lee of the curved cay margin. Thalassia is rooted into the sand in contrast to the majority of the other algae which anchor onto broken fragments of branched coral rubble which are scattered over the sediment surface.

On the open agitated reef flat, the algal assemblage is more diverse and the associated fauna includes molluscs, sponges, holothurians, echinoderms and a wide range of organisms encrusting dead coral (Fig. 8, Plate 8a, 9a). Halimeda and Caulerpa are relatively uncommon except on the outermost algal patches near to the reef edge.

The algae baffle water movement thereby permitting the vertical accretion of hummocky, moderately to poorly sorted, slightly muddy, medium to coarse sand. The sediment is highly bioturbated and contains scattered disarticulated bored bivalves and fragmented encrusted corals. This belongs within the coral-mollusc-skeletal subfacies of the coral-mollusc packstone-rudstone lithofacies (Section 2.6.3a).

(b) Sand Flat

Sand flats are areas of mobile, largely barren and uncolonised shifting sand (Fig. 8, Plate 8b-d), which variously grade into algal flat, the outer colonised moat or intertidal bars. The depth of unconsolidated sand ranges from 5 cm. to greater than 1 metre. These uncolonised patches are composed of coarse sand, rare red algal nodules 20 - 80 cm. in diameter and scattered coral cobbles. The rubble varies from coarse shingle to boulders greater than 30 cm. in maximum dimension. Small patch reefs grow on the sand flat, increasing in size and frequency towards its reefward edge. Patch reefs are from 10 cm. - 1 m. in diameter and are composed of a low diversity coral assemblage (Plate 8d). Montipora ramosa comprises 80% of reef flat corals on Pulau Pari (Brown *et al.* 1982). The corals are bored by the tube worm Sabellastarte indica and encrusted by epilithic organisms.

On barren sandy patches, the echinoderm Diadema setosum commonly clusters in hundreds, forming mobile thickets (Plate 10f) upto 8 m. across, whilst elsewhere holothurians (Plate 8c) rival Diadema in abundance. Near to breaks in the reef edge the sand flat sediment is winnowed and forms a carpet of coarse coral-mollusc grainstone.

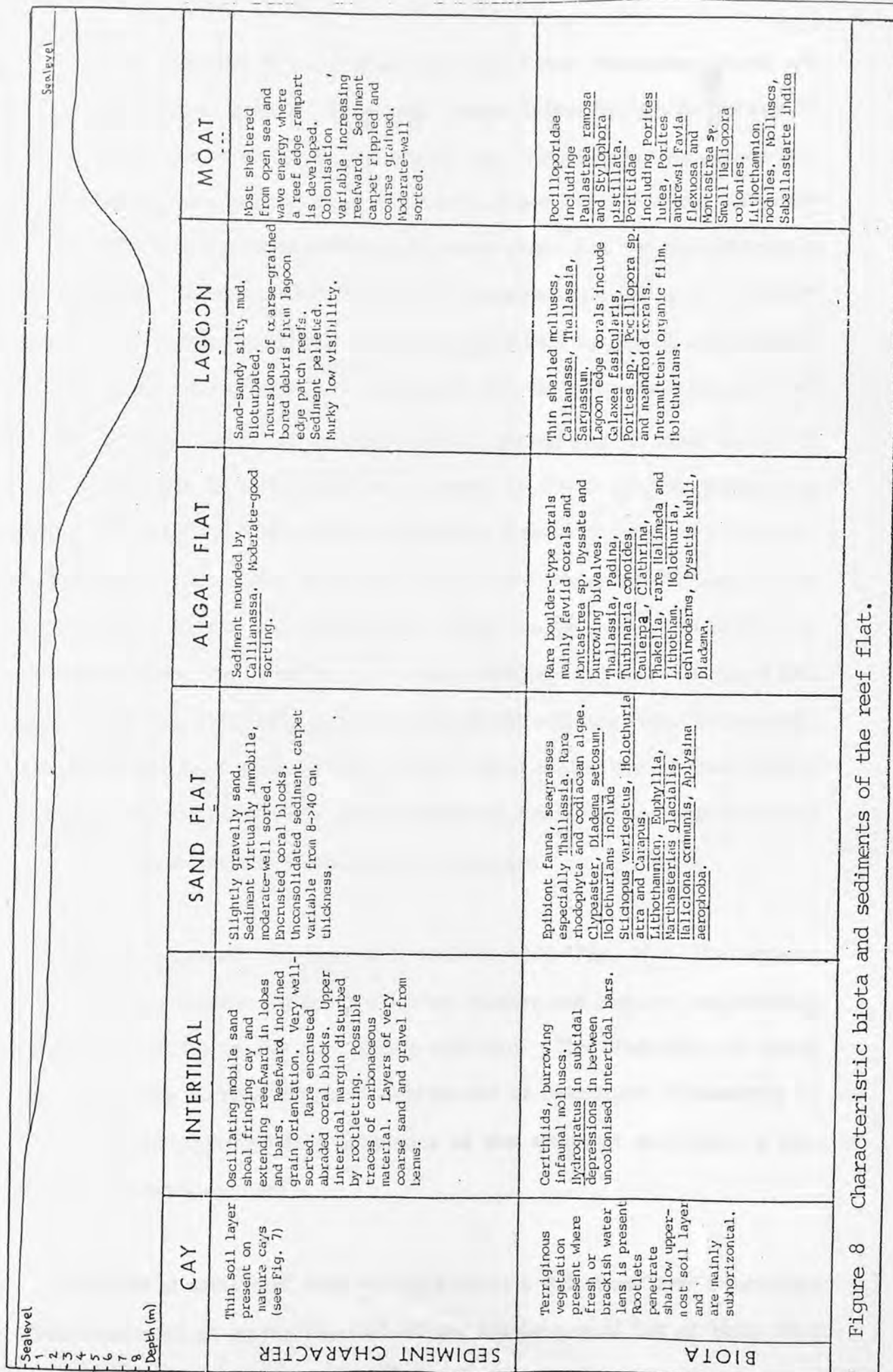


Figure 8 Characteristic biota and sediments of the reef flat.

Parts of the sand flat on Pulau Pari and Pulau Pentundang Kecil are completely covered in conical Callianassa mounds (Plate 9e) which average 35 cm. in diameter and 20 cm. in height (Plate 10e). Adjacent burrows grade into and interfere with one another and in such areas there are few rooted colonisers since the slopes of the mounds continuously suffer small slips and the substrate is highly unstable. Sediment ejected from the exhalent hole drifts in the water column before being redeposited. Roberts et al. (1981) suggested that this is a significant agent of sediment^{transport} and calculated that on intensely burrowed reef flats upto $3.9 \text{ kg.m}^{-2}.\text{day}^{-1}$ of sediment may be ejected 5-10 cm. into the water column. Sediment is bioturbated to a depth of 20-50 cm. by Callianassa (Tudhope & Scoffin 1982) and selective biogenic size-sorting results in textural inhomogeneity. Grains finer than 250 - 500 μm . are preferentially worked into the upper levels of the bioturbated layer whilst coarse grains, predominantly fragmented mollusc shells, collect as a subsurface lag or are incorporated into the stiff mud lining which reinforces the walls of the exhalent vent. Biogenically constructed rosettes of gummed sand are also found around the exhalent hole of Callianassa mounds (Plate 10d). The rosettes are multi-layered, approximately 10 - 12 cm. in diameter and disintegrate on drying out.

Burrows represent special microenvironments (Fig. 9). The organic mucus-mud lining and the fill are of different texture and porosity, and probably different pH and Eh to the surrounding sediment. The production of faecal pellets within the burrow results in aggregation of calcilutite representing an alteration in the hydrodynamic properties of the sediment and hence a new diagenetic microenvironment.

On parts of some reef flats the sand forms a thin cover over a substrate of dead coral such as occurs on much of the northern sand flat of Pulau Pari

Ejected sediment dissipates
and is redeposited downcurrent
from vent.

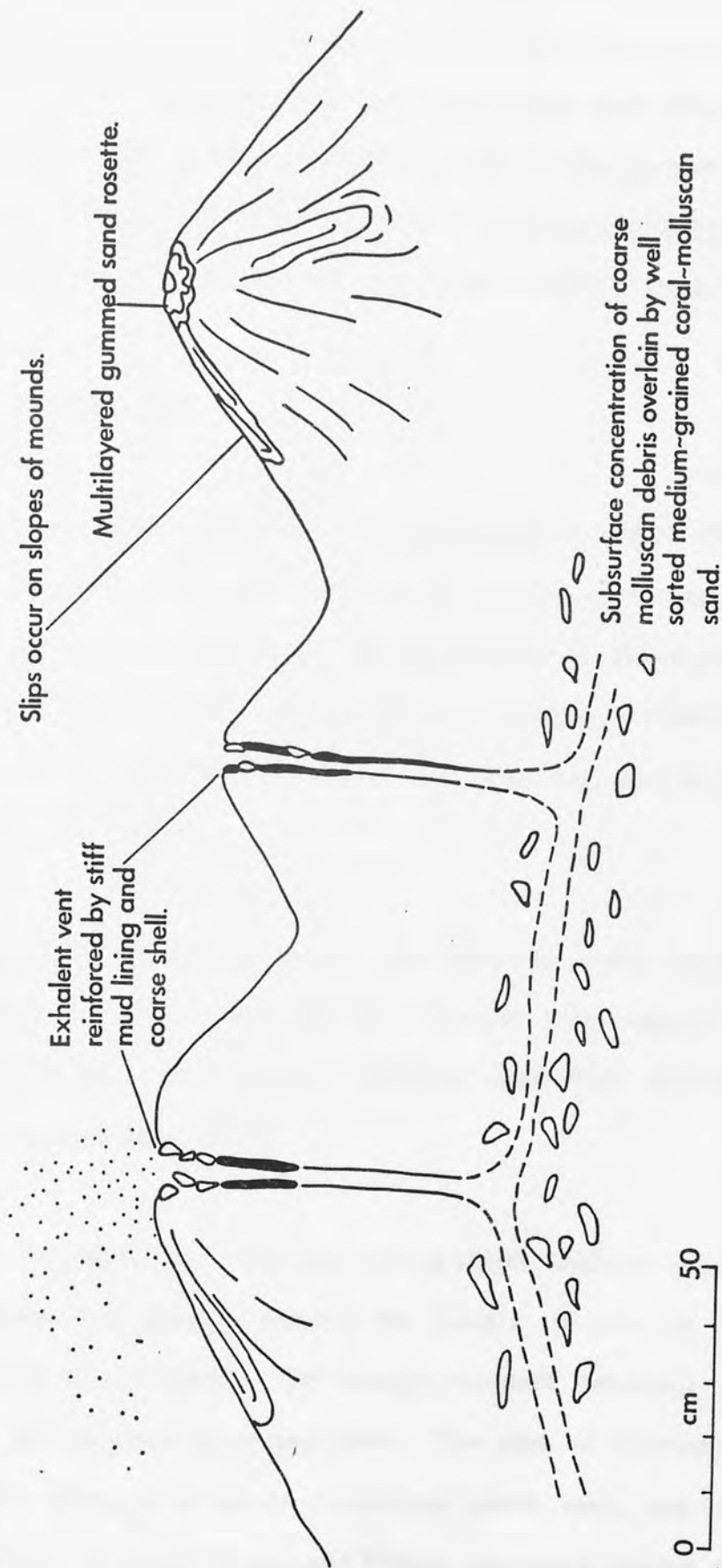


Figure 9 - Microenvironments created by burrowing Callianassa.

(Plate 10a,b). The dead highly bored coral forms small ledges of indeterminate thickness which are found mainly toward the outer part of the reef flat. It may represent a former position of the reef edge or the dead tops of former microatolls. Separating the ledges are areas of deeper sand which represent interstitial sediment infilling the primary cavities of the former reef edge. These inter-ledge patches are colonised by a Thalassia-Caulerpa -molluscan community (Plate 10c), and the ledges by corals and encrusting algae.

(c) Outer Colonised Moat

Inside the reef edge is a slightly deepened trench or "moat" (Brown et al. 1982) colonised by coral patch reefs. Compared with the reef crest, the coral-algal assemblage of the outer colonised zone is low although the alga:coral ratio is higher than on the crest. The fauna and flora are similar to those of the sand flat although a wider variety of corals occur, including several species of Acropora (Fig. 8).

Compared with the shallow inner reef flat, the outer colonised zone provides a habitat for biota which are less tolerant with respect to diurnal temperature and salinity fluctuations. Shallow sand flats undergo diurnal temperature undulations of up to 9°C.

The moat is 0.8-1.1 m. deep and the gradient shallows gradually in a shoreward direction but steeply toward the shingle rampart or crest in a reefward direction (Plate 12b). The shingle rampart generally marks the reefward border of the outer colonised moat. The area of colonisation varies from 50-95% and consists of small interlinked patch reefs and microatolls separated by patches of coral shingle and coarse commonly rippled sand (Plate 9b). Microatolls are circular or elliptical corals 0.4-1.5 m. in diameter,

which are common in the outer colonised moat of reef flats (Plate 9d). The structures are generally monospecific, Heliopora coerulea being particularly common, although small colonies of many other species grow on dead parts of the dominant coral. The margins of microatolls are composed of live coral, and a central depression or hollow forms on the top which is commonly encrusted with algae and sediment. In many respects, these structures represent a microcosm of early reef development (Section 2.7.4).

Sediment of the outer colonised zone is bimodally sorted, comprising a coarse sand fraction, and a less well sorted coral cobble fraction composed mainly of encrusted Acropora branches. The sandy patches are generally only a thin layer, but thick bodies of sand occur rarely and are mounded by Callianassa. Sediment is ingested by holothurians and other sediment-ingesting grazers, which produce strings of cohesive muddy pellets.

The outer colonised moat is not always well-defined, especially in the absence of a shallow or emergent reef rampart zone. Instead there may be a gradual transition from the reef flat to the crest marked by a gradual increase in coral cover and diversity, and depth (Plate 9c).

2.3.3 Lagoon

Lagoons are basins within the reef flat, and are found only on the southern islands of the Pulau Seribu (e.g. Pulau Pari, Pulau Ayer), where they cover upto 60% of the reef area (Plate 2a, 11). Lagoons range from 20-1000 m. in maximum dimension, 3-12 m. in depth and are elliptical or irregular in shape; elliptical lagoons generally have borders parallel to the reef edge. Entrances to lagoons are considerably shallower than the lagoon itself, but eddies caused by the movement of water past the reef, and rapid exchange of water between the

lagoon and open sea prevent the build-up of a stagnant hypersaline water mass. The temperature of the lagoon floor is stable at 28°C but mixing is thorough and surface water temperature rarely differs by more than 0.75°C.

Lagoon boundaries shallow rapidly (Plate 11a-b) and this is accompanied by a transitional coarsening in mean sediment grain size towards the reef flat. The slopes of lagoon margins are sometimes colonised by patch reefs (Plate 11b), which result in local accumulations of coarse detritus. Lagoons are flat-bottomed or trough-like in profile and coarse lobes of sediment avalanche down the lagoon slopes. Sediment on the lagoon floor is sorted by bioturbation, and consists of sandy silts and muds which are commonly pelleted by infauna and belong to the sparsely bioclastic bioturbated pellet-mud lithofacies (Section 2.6.3d).

Sorting is moderate and the only coarse fragments present are rolled downslope from patch reefs and are therefore restricted to lagoon margins, and to local postmortem accumulation of in situ benthos. The coarse clasts suffer no wave abrasion in this low energy environment, but they are intensely bored. The degree of abrasion is a distinct contrast between lagoon and reef flat environments.

The lagoon contains a very low diversity fauna and flora. Shallow sandy lagoon floors and shallow slopes are colonised by Diadema. Elsewhere anchored or floating clumps of Sargassum occur. Callianassa inhabit the muds together with a sparse molluscan assemblage including thin-shelled bivalves, and rare Holothuria atra. Besides Callianassa, other arthropods which were not collected for identification, construct reinforced burrows 4 cm. in diameter, which penetrate vertically down into the undulating lagoon floor. The turbidity of bottom water inhibits colonisation by photosynthesising or filter feeding

organisms, visibility commonly being below 0.2 m. Thin brown-coloured cyanophytic algal films bind the muds intermittently but these are disrupted by burrowers and grazers, and by the long-bladed Thalassia which colonises the margins of the lagoon floor.

Patch reefs rim the Pulau Seribu lagoons in small cliffs rising in a vertical wall from a depth of 9 - 2m. The individual patch reefs are 3-12 m. in maximum dimension and frequently interlink to form a reticulate pattern around the lagoon margin (Plate 11b,c). A large-scale reticulate growth pattern was described from Belize (= "rhomboid reefs" of Ginsburg & Choi 1983), and attributed to renewed reef growth on local elevations of pre-Holocene karstified limestone. The reticulate reef pattern of the Pulau Seribu is less deeply-rooted and the cause may be local pooling of stale waters on the reef flat at low tide.

Commonly the lagoon margin coral thickets are upto 80% dead and alga-encrusted but dead substrates are often subsequently colonised by new corals. Unsorted mud, sand and shingle partly fill the interstices which are inhabited by cave-dwelling fauna. Fig. 8 lists the prevalent fauna of the lagoonal zone. The margins of the lagoon grade into the reef flat across an algal-rubble zone. This transitional zone is colonised by boulder corals, sponges, holothurians, molluscs, crustaceans and Thalassia. The Thalassia thickets and coral colonies act as baffles which inhibit movement of sediment from the reef flat into the lagoon.

2.3.4 Shingle Rampart

The shingle rampart (= "zone of cobbles" described by Braithwaite 1972 from Seychelles) borders the northern, western and eastern margins of wave-exposed islands such as Pulau Belanda, Pulau Pari, Pulau Petundang Kecil (Plate 13a). It is a wave-accumulated bank composed exclusively of recently detached

lumps of coral (Plate 12d). Much of the coral in the subsurface part of the rampart, is intensively bored and encrusted. Acropora hyacinthus which thrives on the reef crest (Plate 12c) is easily broken by shoaling waves and constitutes a large proportion of rampart detritus. Rampart sediment belongs in the coral cobble rudstone-grainstone lithofacies (Section 2.6.3c).

Most shingle ramparts are periodically submerged at high tide but, on a few islands subjected to persistent storm activity, ramparts which are permanently subaerially exposed have developed, for example at Pulau Peniki. Figure 10 illustrates the characteristics of reef edges with permanently emergent and periodically submerged shingle ramparts. Where present, the emergent bank is 5-15 m. wide and rises upto 0.5 m. above low tide. The rampart shelves off sharply shorewards into the outer reef flat (Plate 12b), and slopes gradually reefwards into the submergent shallow wave-surge portion of the rampart (Fig. 10). The latter consists of a carpet of coarse winnowed coral branches and coral shingle often thickly colonised and bound by the algae Halimeda tuna, Caulerpa racemosa, Turbinaria and rarely Padina and rhodolithic algae (Plate 12a, 14b). The algal assemblage forms mats which prevent erosion of loose rubble and stabilise the sandy-rubble substrate. This environment is highly turbulent and not conducive to coral growth. Reefward it grades into the crestal zone with a gradual increase in number, size and diversity of corals. Low flat corals such as the aforementioned Acropora hyacinthus and Montipora foliosa colonise this periodically very shallow area, together with small faviid and Porolithon corals which nestle between rubble. Sediment fines reefward and symmetrical oscillation ripples 2-3 cm. in amplitude, straight- to arcuate-crested and with a wavelength of 0.5 m., form in the course 4-7 cm. thick sand carpet. The ripple troughs are filled with a granular lag or sometimes expose the coral rock substrate beneath.

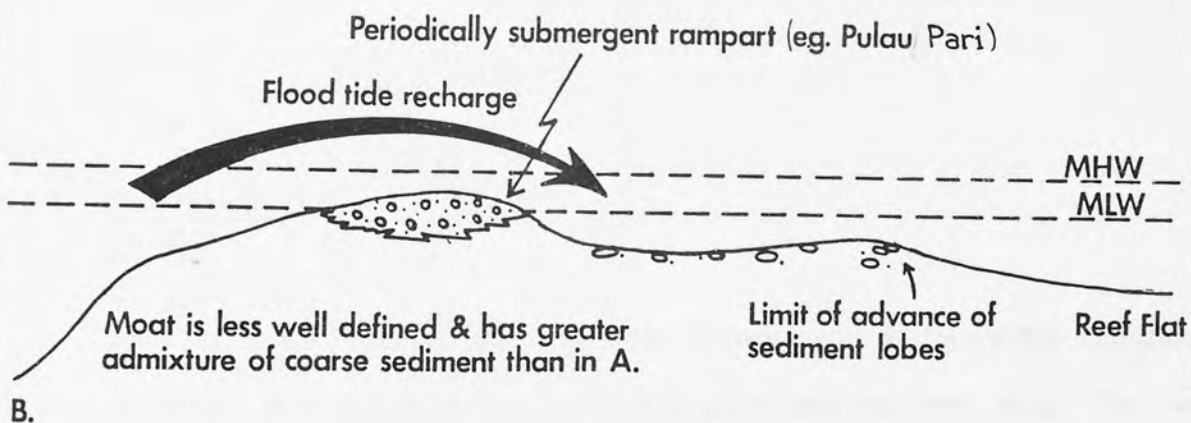
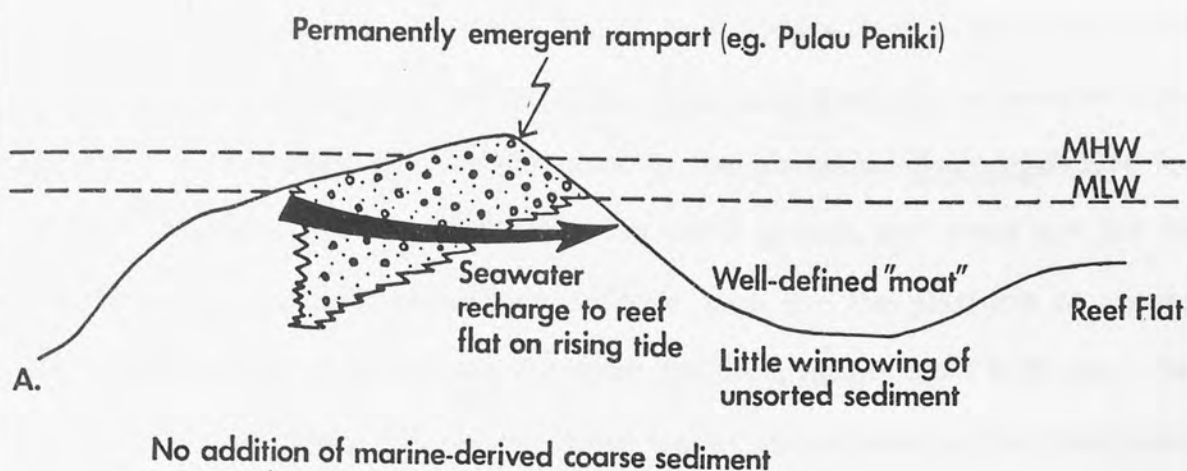


Figure 10 - Morphology of permanently emergent and periodically emergent shingle ramparts.

Occasionally shingle ridges form considerably shoreward of the reef edge and inside an outer shingle rampart. Such a situation occurs on the eastern reef flats of Pulau Petundang Kecil and Pulau Ayer (Plate 11d). Elevated coral shingle bars on the outer reef flat of Pulau Petundang Kecil are orientated sub-parallel to the reef-edge and are colonised by the mangrove *Avicennia* (Plate 2c, 7a). The mangroves grow individually or in small groups, and trees are 2-3 m. high. The water depth of these inner shingle bars, and the platform of coarse coral shingle separating them from the outer rampart, ranges from 8-30 cm. The inner bars were probably formed by storm waves which broke across the outer rampart.

Ramparts are discontinuous along less exposed parts of the reef, particularly in embayed sections of the reef edge (Fig. 19). Where the rampart is absent, the reef flat grades into the crest through a moderate diversity coral-algal assemblage.

2.3.5 Reef Slope

The reef slope represents the growing framework of the reefal complex. It is subdivisible into the reef top or crestal zone and the reef wall. The two sub-zones are separated by a break in slope which generally occurs at a depth of approximately 4 m. The crestal zone slopes gradually and irregularly from the outer limit of the reef slope or shingle rampart, at a gradient of $5-10^{\circ}$ to the reef wall which drops off sharply at between $45-75^{\circ}$.

(a) Crestal Zone

The crestal zone is a gently shelving platform which borders all reefs. The reefward boundary is transitional and defined by increasing depth, decreased

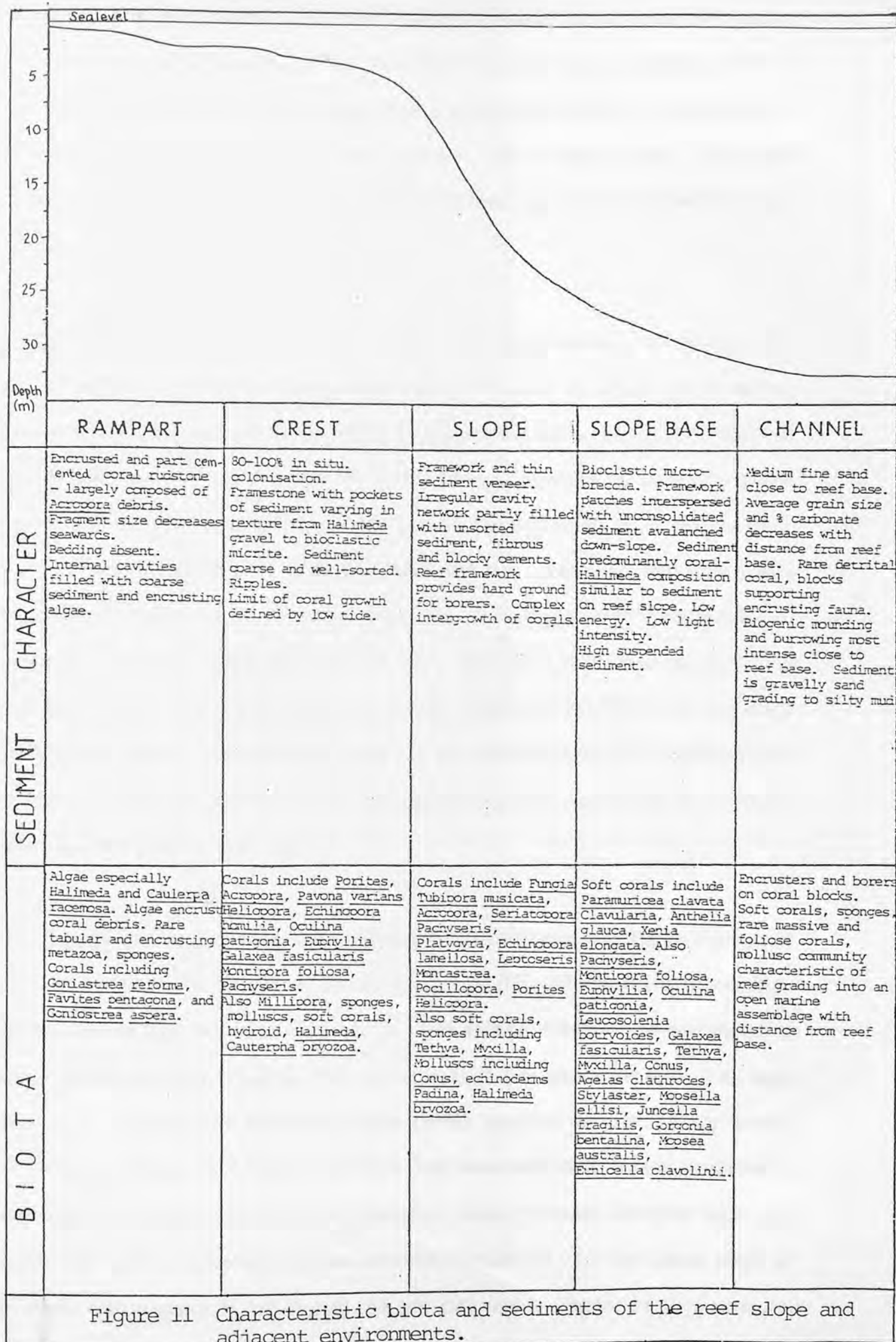


Figure 11 Characteristic biota and sediments of the reef slope and adjacent environments.

turbulence, increasing faunal and floral cover, increase in the sand:rubble ratio and increase in the coral:algal ratio. The crest is narrow in plan ranging from 3-15 m. in width, widening at the eastern and western extremities of the reef as a result of the preferentially higher coral growth rate in those areas. The wide flat platform serves to dissipate wave energy across the crest. The depth ranges from just subtidal to 9 m.

Faunal and floral diversity increases from the shallow boundary of the crest to attain a maximum just above the reef wall at which point strong currents are present but growth is below average wave base. Loya (1972) showed that physical parameters are the most important influence in structuring the reef crest community and that the highest diversity will occur in an environment which suffers intermediate strength, intermediate frequency "catastrophes", such as storm agitation or subaerial exposure. Umbgrove (1947) recorded 120 species of coral from the Pulau Seribu-Jakarta Bay area, and Brown et al. (1982) identified 88 coral species of 28 genera on the peripheral reef flat and reef edge of Pulau Pari alone. Seventy-four species were recorded from the southern reef flat and 43 from the northern reef flat suggesting that conditions on southern flanks favour a greater diversity.

In addition to increased coral diversity on southern reef flanks compared with that to the north of islands, Brown et al. (1982) noted a positive correlation between percentage cover and diversity. The crestal substrate is composed of large interlinked coral colonies, commonly in cliff-like pedestals upto 5 m. high (Plate 14a, c) dead reef substrate, loose rubble patches and rare sandy areas. The irregular shape of colonies controls the near-substrate water movement, dissipates wave energy and baffles currents. Coral colonies compete with one another for space, and overgrow one another (Plate 15). At the upper limit of the crest, corals grow to just below the low tide level. Figure 11 lists common

members of the crestal faunal assemblage. The massive coral Porites lutea provides a favourable substrate for a variety of boring filter-feeding organisms and encrusters (Plate 14a-c, 16b,) such as Sabellastarte indica and the Serpulidae. The boring bivalve Pedum spondylioideum embeds itself in the coral, and Tubastrea aurea, red algae, sponges and didemnids encrust the overhanging undersides of colonies (Plate 16b). Circular protuberances on the coral indicate the presence of barnacles which have been grown over by the coral. A variety of fish and encrusting organisms inhabit cavities in the reef.

The percentage of sediment cover on the crest is low. Abiogenic sedimentary structures include ripples, grooves and depressions. Ripples occur rarely in the transition between rampart and crest. Grooves upto 1 m. wide occur (Plate 15c) between the massive coral pedestals and are commonly orientated perpendicular to the reef edge. This may be an embryonic type of spur and groove development although well-formed examples are not encountered in the Pulau Seribu. Grooves channel unconsolidated sediment and are carpeted by continually oscillating coarse sand and gravel, and the margins are colonised by small clumps of branching coral such as Seriatopora. The grooves sometimes funnel reefward into sand falls or rubble chutes, which are 1-10 m. wide, widening downslope. They are colonised by vagrant benthos such as the solitary coral Fungia fungites, gastropods, bivalves and echinoderms. The sediment is derived from abrasion of reef-top colonies and Halimeda (Plate 13c-d) often comprises a very large proportion (90%⁺) of the sediment (Section 2.6.3b).

Depressions on the reef crest are shallow scours generally encrusted with algae and a thin sediment veneer. Scoured rocky slabs ranging from 50 cm. to several metres across are the remnants of thick tabular colonies and are probably in situ.

(b) Reef Wall

Downslope the prolific growth of the crest gives way to more irregular growths of live coral interspersed with sediment pockets. The coral assemblage itself also gradually changes with depth. Figure 12 illustrates the modifications in areal coverage of live and dead coral and unconsolidated debris as a function of water depth.

The reef wall slopes from a depth of 4-9 m. to the reef base at approximately 20-28 m. (Fig. 13). Its major axis parallels the edge of the reef plateau. The lower limit is defined not only by a break in slope but also a rapid decrease in the area of stable colonised substrate. The reef wall is approximately 20 m. wide in plan, thus the areal extent is considerably surpassed by the reef flat.

The fauna is highly diverse (Plate 14d, 15b, Fig. 11), peaking at the top of the reef slope (Plate 15d) where there is 80-100% colonisation, and decreasing downwards. The top of the reef slope is at or just below wave base. The main reef framebuilders are corals which are sometimes bound by algae and minor amounts of bryozoa and sponges.

The reef wall is very open textured with good circulation and an irregular profile. The size of cavities ranges from a few millimetres within individual corals, to several metres between overlapping colonies. Cavities are partially infilled with unsorted coarse sands, muddy sands, disarticulated coral branches, encrusting organisms and comminuted skeletal debris. Sand and rubble are interspersed with the live coral. Figure 12 suggests that reef walls at exposed sites have a relatively high areal percentage occupied by sand and rubble

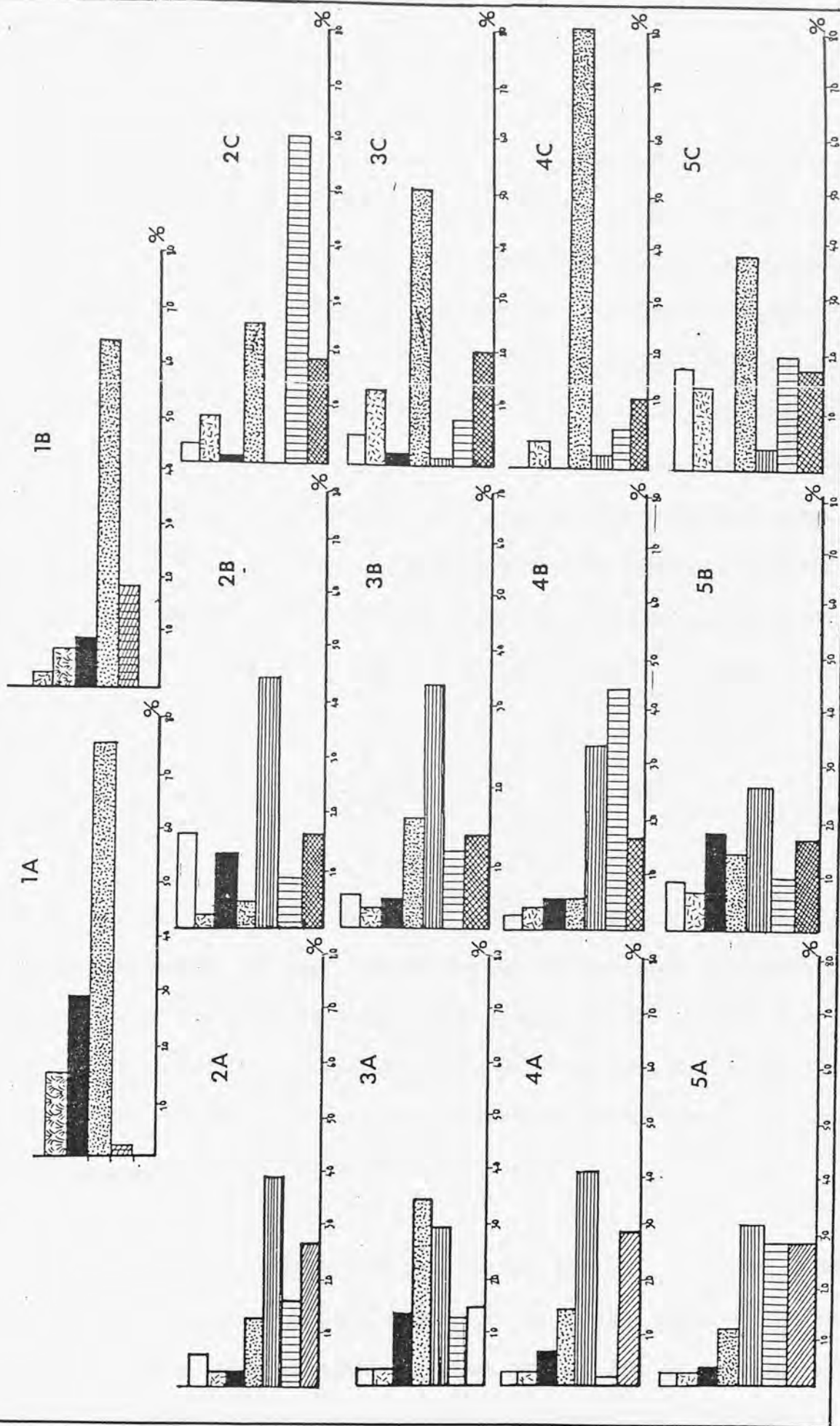











Figure 12. Percentage of area covered by live and dead biota and unconsolidated sediment related to depth and exposure.

	Unconsolidated sand and rubble
	Branched coral
	Foliose coral
	Massive coral
	Undifferentiated coral
	Algae
	<u>Thalassia</u>
	Sponge
	Hydroid, anenomae, soft coral

- 1A** Pulau Petundang Kecil inner reef flat SE of cay
1B Pulau Petundang Kecil mid reef flat SE of cay
2A Pulau Pari, southern flank, 3 m. depth. Sheltered site.
2B Pulau Pari, southern flank, 10 m. depth
2C Pulau Pari, southern flank, 20 m. depth
3A Pulau Ringit, eastern flank, 3 m. depth. Exposed site.
3B Pulau Ringit, eastern flank, 10 m. depth
3C Pulau Ringit, eastern flank, 20 m. depth
4A Pulau Petundang Kecil, eastern flank, 3 m. depth. Exposed site.
4B Pulau Petundang Kecil, eastern flank, 10 m. depth
4C Pulau Petundang Kecil, eastern flank, 20 m. depth
5A Pulau Petundang Kecil, eastern flank, 3 m. depth. Sheltered site.
5B Pulau Petundang Kecil, eastern flank, 10 m. depth
5C Pulau Petundang Kecil, eastern flank, 20 m. depth

compared with sheltered sites.

Unconsolidated material occupies channel-like chutes 5-30 m. wide, which are orientated at a high angle to the reef edge (Plate 1, 11f). The surface of sand falls is irregular and mounded by burrowing infauna. Due to the downslope settling of suspended sediment ejected from burrows, the mounds are commonly assymmetric, "trailing" downslope. Heaps of rubble on the sand fall form small step-like features. Sand and rubble chutes are slightly sinuous and frequently bifurcate at the upper end where they are fed by smaller chutes. The avalanche does not always continue to the reef base but commonly terminates in a fan on the reef slope. The sands are unstratified and sometimes pelleted. Sediment on the reef slope and reef crest belongs within the coral-mollusc packstone-rudstone (Section 2.6.3a) and coralgal packstone grainstone (Section 2.6.3b) lithofacies.

2.3.6 Reef Base

At the base of the reef wall is an apron of coral-skeletal debris which grades downslope into the deep forereef channel environment. The upper and lower boundaries are gradational, defined by gradual changes in slope (Fig. 13) and decreasing colonisation. The width of the transition zone varies from 10-25 m. The depth range of the reef base environment is variable from 19-34 m. and the average gradient is 20° flattening downslope to 5°.

The reef base is composed of reef-derived detritus in a series of sub-parallel lobes issuing from sand and rubble falls on the reef slope. On the reef slope, rubble falls are channelised by coral colonies but as colonised area diminishes downslope, the sediment fans merge with each other. The sediment is an unsorted mixture ranging from cobble-size coral, to silty mud, deposited from

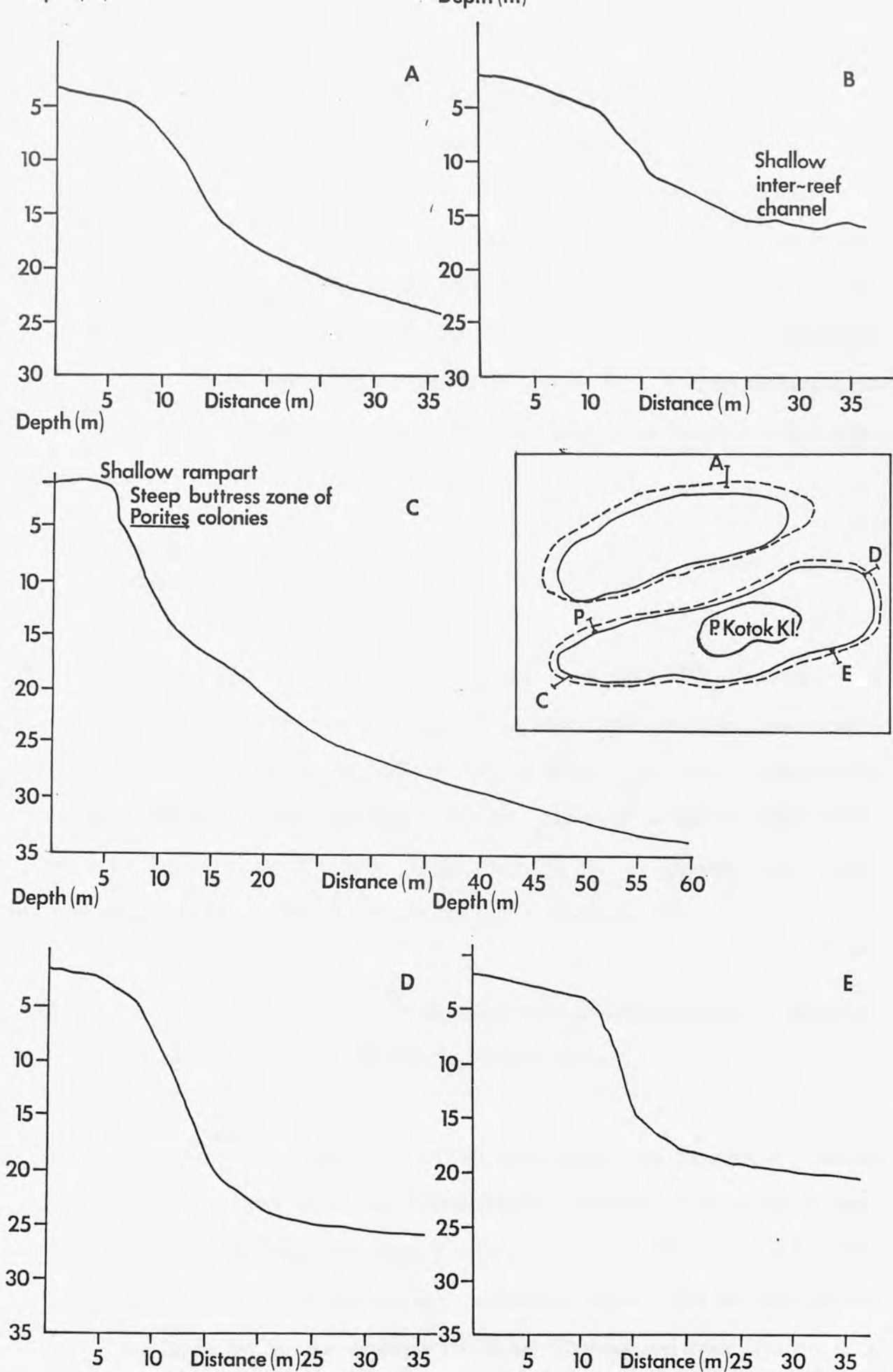


Figure 13 - Profiles of the reef slope at Pulau Kotok Kecil.

suspension, with a large admixture of Halimeda gravel. The surface of the sediment pile is loose and colonised intermittently by gorgonians and alcyonarians (Fig. 11, Plate 16d,17). There are also patches of colonised reef detached from the mean reef wall. The size and frequency of these patch reefs diminishes rapidly downslope and the faunal diversity is low compared to the reef wall environment. Branching corals are rare, most corals in this environment having flat, platy or encrusting morphologies (Plate 17a). A large surface area-to-volume ratio is an adaptation to the low light intensities at depth where there is no necessity for robust skeletal structures.

2.3.7 Channel

Channel sediments are largely noncarbonate but this environment is included in the reef description since, if the area was fossilised, the channel would represent an integral part of the reef complex (Cook 1982). Channels are the deep forereef areas between the reef bases of adjacent patch reefs. Distances between patch reefs range from 50 m. to greater than 3 km. Morphologically, channels are subdivisible into two types;

- (a) Narrow channels which are usually orientated approximately east-west and are 26-35 m. deep and 20-300 metres wide.
- (b) More basin-like areas of sea floor which are often considerably deeper than the narrow channels. These separate the more isolated patch reefs and range in maximum depth from approximately 32 m. exceptionally to 68 m. These wide channels are encountered more in the southern part of the Pulau Seribu, for example the Outer Channel and Inner Channel (Fig. 3).

In cross-section, channels have a gentle U-shaped profile sloping down from the reef base at a gradient of 3-15° asymptotically decreasing toward the centre of the channel. In plan the channels are slightly sinuous and interlinked with one another by connecting passages between patch reefs. The channel floor is mounded by infauna at the margins, although the central part of wide channels is featureless.






2.4 BIOEROSION

Bioerosion is quantitatively the most important process responsible for denuding reefs (Trudgill 1985). Its effects are most intense in deep water where there is a high percentage of dead surface area. Bioerosion refers to sediment breakdown resulting from the boring, scraping and ingesting activities of both vagrant and sessile reef dwellers. The main agents of bioerosion are sponges, echinoids, molluscs, tunicates, fungi, algae, polychaetes and fish (Plate 16a). Their roles in the reef system were reviewed by Warne (1977) and James (1982).

The chipping-off of fragments from a relatively large coral colony or the fragmentation of a mollusc through boring results in a significant contribution to the mud and silt sized fraction of the sediment, and the presence of macro- and micro-borings result in considerable porosity increase within the reef framework (Fig. 14). Furthermore, bioerosion weakens a carbonate structure rendering it more vulnerable to mechanical erosion.

The cumulative destructive effect results in the creation of a honeycomb-like network of passages supported by old borewalls and residual host substrate (Plate 18a,c,f, Fig. 14). In some places, particularly around the margins of a coral, the linings of adjacent borings are in direct contact and no intermediate original substrate remains. Ultimately, all of the substrate is obliterated and composed of secondary bored pores maintained by a delicate mesh work of fine



- s sipunculid boring
 b characteristic circular cross-section of bivalve boring
- | | |
|---|-----------------------------|
|  | coral |
|  | cavity |
|  | bound sediment |
|  | undifferentiated encrusters |
|  | <u>in situ</u> bivalve |

0 1 2
 cm.

Figure 14 Section through a bioeroded coral.

and relatively insoluble organic linings (Plate 19c). These organic rinds divide up large pores and trap fine washed-in sediment. Often sticky mucus strands bridge pores. Some biogenically lined borewalls are unpunctured and seal off the internal passageways hence creating a sheltered microenvironment within which organic material decomposes and stale water may become trapped.

In this study four main types of boring were recognised;

- (a) sponge borings with characteristically scalloped margins
- (b) bivalve borings
- (c) polychaete or sipunculid borings
- (d) microborings.

(a) Sponge borings

Boring sponges are ubiquitous on coral reefs and excavate galleries 0.15 - 1.5 mm in diameter which penetrate 0.5 - 80 mm into the substrate (Wilkinson 1983). Sponges, particularly Cliona species are the most important bioeroders in terms of volume removed. The intensity of boring is affected by such diverse factors as light, current strength, substrate character and availability, temperature and competition (Ruetzler 1975). A number of quantitative studies of their importance have been made (Hein & Risk 1975; Ruetzler 1975; Stearn & Scoffin 1977; Hudson 1977; and Bromley 1978). MacGeachy (1977) concluded that sponges account for more than 90% of total boring in most coral heads, the volume removed in deep and shallow water environments ranging from upto 23% and upto 11.6% respectively of original carbonate volume. Moore & Shedd (1977) calculated that 2-3% of the bored substrate is dissolved by the sponge and the rest of the excavated mud- to silt-sized material (15-100 μ m) is ejected by the pumping of the organism. This sediment is winnowed from relatively high energy parts of the reef and redeposited in quiet areas of lost from the system



- s sipunculid boring
 b characteristic circular cross-section of bivalve boring

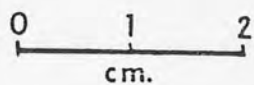
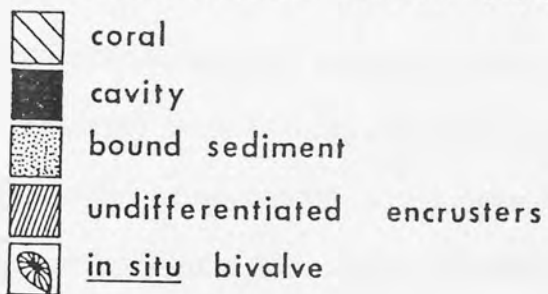


Figure 14 Section through a bioeroded coral.

(MacGeachy 1977). Futterher (1974) reported that 30% of the sediment on parts of Fanning Atoll in the Pacific Ocean, was composed of sponge chips, and estimated that 10% of the 20-63 μm fraction of sediment in the Northern Adriatic and Persian Gulf was derived from the activity of sponges.

Neumann (1966) calculated that sponge boring in Bermuda was equivalent to an erosion rate of one metre per seventy years. However, Ruetzlers() experiments suggested that the rate of sponge boring in a substrate tends to undergo an exponential decrease over time. Studies conducted by Stearn & Scoffin (1977) and Morre & Shedd (1977) indicated drastically lower estimates of rate of sponge bioerosion ($8-382 \text{ g.m}^{-2}.\text{yr}^{-1}$ and $1-1.8 \text{ kg.m}^{-2}.\text{yr}^{-1}$ respectively) compared with Neumann (1966) estimate of $6-7 \text{ kg.m}^{-2}.\text{100 days}^{-1}$.

The inconspicuousness of sponges is due to their cryptic habitats which are mainly concentrated in dead marginal parts of coral growth framework such as the base of colonies or on patches which have been scraped free of live coral by the scraping activity of other agents of biological erosion. Many cavities of indeterminate origin and also some abandoned mollusc borings examined had etched walls suggesting colonisation by sponges.

(b) Bivalve borings

Bivalve borings have a circular cross-section approximately 1 cm. in diameter and a curved or bullet-shaped long-section. Borings are blunt-ended, commonly display scalloped walls (Plates 19b,21c) and are often lined with a cryptocrystalline, organically-precipitated, smooth whitish-grey coating. In several slabbed cores examined, the boring bivalve Lithophaga was encountered in situ.

Most borings however, are unoccupied and cross-cut the coral structure

often expanding from a small opening on the coral surface into a large cavity within the colony. Vacated cavities are often part-filled with well-sorted to unsorted slightly muddy coarse sand. Foraminifera, echinoid and mollusc fragments, sponge spicules, faecal pellets and mud are carried into bioeroded crevices within the reef by the pumping action of swell. Thin section examination reveals that once the bivalve is dead or has bored deeper into its substrate, the macro-borings provide a niche for new bioeroders. Smaller bivalve borings commonly lead off from a large main cavity and algal or fungal encrusters line the old walls. Small calcareous crusts of serpulids coat the inner lining of some bivalve borings, appearing as an encrustation of spiralling white tubes.

(c) Polychaete or sipunculid borings

These borings are uniformly 1 mm. in diameter and have a circular cross-section (Plate 18). The bore walls are coated with a relatively thick apparently impermeable brownish-cream micritic lining. The coat is smooth, opaque-to-translucent and glossy. The borings often emanate from a bivalve-excavated cavity and are generally orientated approximately perpendicular to the direction of corallite growth.

(d) Microborings

Microbores 40-120 μm long and a few microns in diameter are interpreted to have been produced by photosynthetic cyanophytes, eucaryotic green and red algae and heterotrophic fungi (Friedman et al. 1971; Alexandersson 1972a; Golubic et al. 1975). Recent study has shown that these biota are important agents of bioerosion (Kloos 1982). The thread-like bores (Plate 19c, e, 20a-b) are a few microns in diameter, straight-sided, anastomosing or U-shaped.

In section they appear as dark-walled vermicular bores, commonly part filled with black clots of fine sediment or organic residue. The bore terminations are rounded. In places, particularly near to the margins of the coral or adjacent to macrobores, the density of the fine interconnected bore network is extremely high comprising more than 80% of the cross-sectional area (Plate 19c). Near to the coral margins and lining macrobores, the fine bores lose any degree of orientation and appear as tangled disorganised threads. Once within the highly bored periphery (15-30 μm thick) orientation is quite regular and generally approximately radially arranged with respect to the outer surface of the host. The transition between the marginal highly bored zone and the less bored interior is gradual. An intensely microbored layer is sometimes present beneath an outer clear relatively unbored layer of coral (Plate 19a) suggesting that boring is intensified in peripheral regions during periods of non-growth.

Microborers also attack molluscs residing in macrobores within the corals. The fine bores penetrate the outer prismatic layer of valves, but are most prevalent in the subsurface laminar layer. The laminated microstructure merges into a cloudy-looking micritised layer 20-30 μm in thickness, composed of L-shaped and dendritic excavations which obliquely cross-cut the skeletal fabric.

Encrusters

Encrusters such as algae, bryozoa, sponges and byssate bivalves are common on the surfaces of corals and molluscs and often block entrances to unoccupied boreholes. These encrusters create a favourable microenvironment for chemical dissolution of the substrate (Plate 19d, f). Coral breakdown close to the surface of the colony is attributed largely to organically derived acids. Biological breakdown resulting from encrustation near to the bases of branched corals leads ultimately to the disintegration of the colony. If the organic encrustation is drawn away with tweezers, the exposed underlying coral surface

appears glossy and irregularly marked with scalloped surfaces. Surfaces beneath encrusting sponges are pockmarked by numerous dish-shaped shallow excavations 0.5-1 cm. in diameter. The boundary between the coral and encruster is often a partly leached cavity transected by thin aragonite and organic bridges and partly-filled with sediment.

Calcareous encrusters such as Lithothamnion (Plate 20c) are themselves bored. Within the algal layers, high concentrations of black-lined microborings are visible, particularly near to the contact between the algae and coral or mollusc substrate. Microbores within these layers tend to be orientated approximately parallel to the coral surface. In highly bored samples the outer margin of the substrate is indistinguishable and merges into the network of dendritic bifurcating bores invading the encrustation (Fig. 14).

The thickness of encrusting layers varies from a few microns to several millimetres. The water-saturated porous leathery mat is often partly clogged with fine-sand, and sediment grains (Plate 20d). Sponge spicules and needle aragonite cling to the bristly or filamentous outer surface. Dead encrusters provide a substrate for colonisation by new borers or encrusters. Often several types of algae encrust one another. Renewed coral growth may occur on top of encrusting layers resulting in an end product of interstratified corals and algae.

2.5 COMPARISON WITH RECENT ENVIRONMENTS OF REEF GROWTH IN NORTH AND SOUTH SULAWESI, INDONESIA

Short visits were made to two locations in order to compare the Pulau Seribu reefs with other areas of present-day carbonate deposition: Pulau Bunaken and the surrounding islands in North Sulawesi, and the Sangkurang Archipeligo in South Sulawesi.

2.5.1 North Sulawesi

The area visited is located off the north-west coast of North Sulawesi at latitude $1^{\circ}40'N$ longitude $124^{\circ}45'E$. Reefs encircle the islands of Bunaken, Manado Tua, Manterawu, Siladeng and Nain. Manado Tua commands the greatest relief rising to 822 m. above sea level. Substantial freshwater vadose and phreatic zones are present on all islands and runoff is likely to affect reef growth. The islands around which the reefs grow are volcanic, in sharp contrast to the Pulau Seribu which are totally carbonate systems surrounded by fine-grained terrigenous sediment. Most of the volcanoes are dormant or inactive except for Manado Tua which erupted in the early twentieth century. Dead, uplifted and weathered Recent reefs form low cliffs on Pulau Bunaken, Siladeng and the mainland (Fig. 15), and are evidence of relatively recent basement movement. The shelf bordering North Sulawesi and in which the volcanic islands are rooted is between 687-1865 m. deep and drops off westward into the Macassar Trench.

Surrounding the islands of Bunaken, Manterawu and Nain, are platforms between 1-5 m. in depth characterised by fine sediments which are largely terrestrially derived. The platform isolating the reef from the island and associated fluvial runoff is more than 1 km. wide around Nain (Fig. 15). A few accumulations of reef-derived rubble support small patch reefs within this lagoonal area, which is bounded on the seaward margin by a periodically emergent rubble rampart similar to that described in section 2.3.4., but lacking the steep shoreward slope. The rampart protects the growing reef from incursions of fine sediment.

With respect to coral growth the water quality around these North Sulawesi reefs contrasts favourably with that encountered in the south-west Java

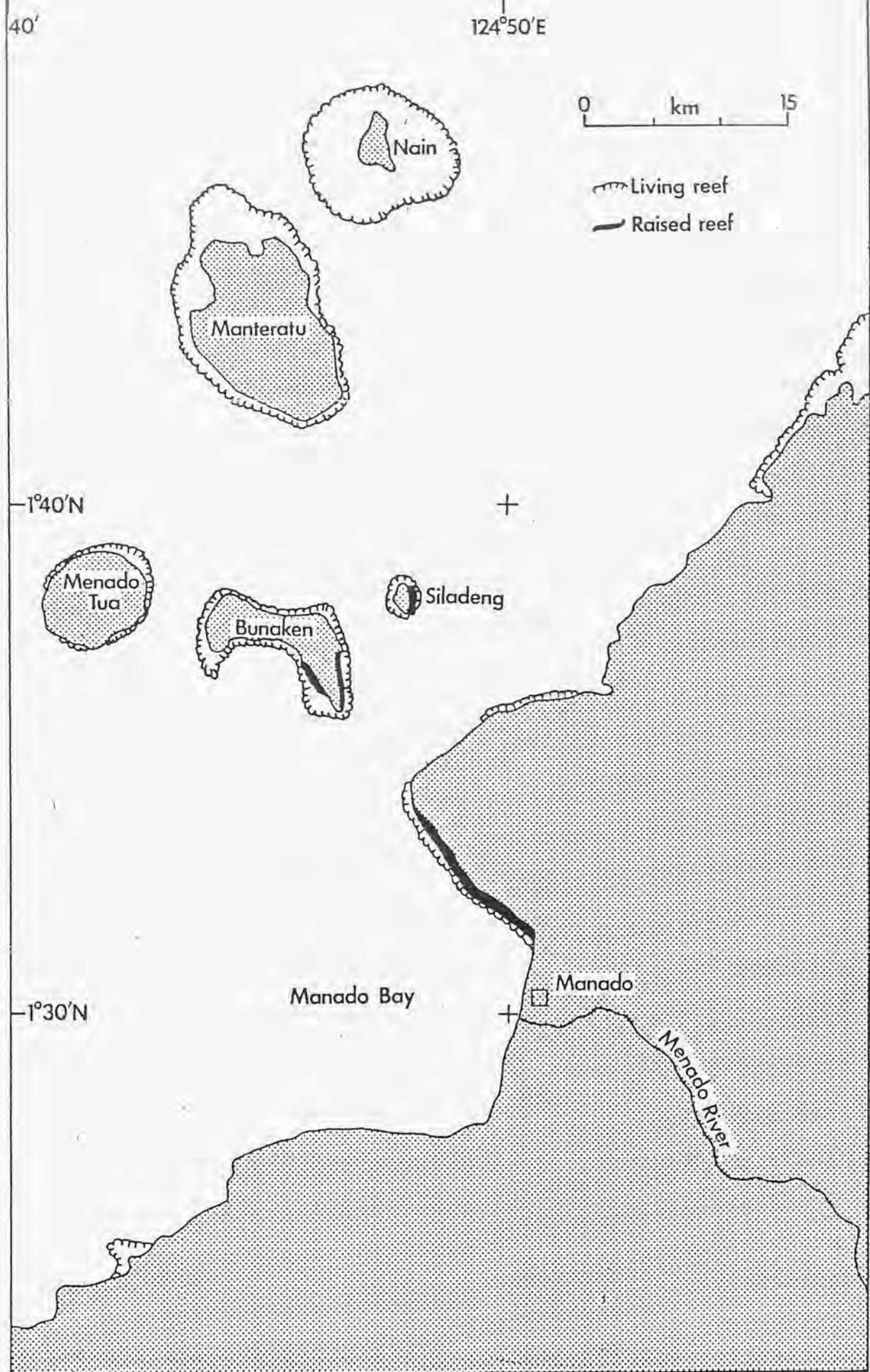


Figure 15. Recent reefs in North Sulawesi

Sea and South Sulawesi. A high content of suspended sediment in the waters surrounding the Pulau Seribu generally reduces visibility to around 7-12 m., whilst visibility attains 45 m. around Pulau Bunaken. This contrast in light penetration due to suspended sediment may be a consequence of the difference in depth of the seafloor. In the Pulau Seribu, current and storm activity are responsible for resuspending channel floor sediments whilst in North Sulawesi, the only source of suspended sediments is from the runoff from islands. In response to the greater depth of light penetration and deeper seabed, corals are found growing to considerably greater depths than in the south-west Java Sea and Sanghurang Archipelago reefs. An Acropora-dominated coral assemblage similar to that described from the crest and upper slope of the Pulau Seribu (Section 2.3.5.), is present to a depth of 30 m. There is a gradual transition to a faunal assemblage characterised by massive corals, including

species of Porites, and alcyonarians, which colonise the reef wall to depths exceeding 50 m. The main contrast in reef slope cover, apparent between the North Sulawesi reefs and the Pulau Seribu, is the considerably higher percentage of in situ cover in the former. Sediment on the reef slope to a depth of 50 m. is restricted to small pockets on ledges. The reefs of Bunaken in particular, are steeper-sided than the Pulau Seribu reefs, the reef wall dropping almost vertically to between 50-58 m. where there is a break in slope. The reef was not explored below this depth due to the restrictions of SCUBA diving. The steep gradient of the reef wall suggests that the predominant direction of growth is upward with negligible seaward progradation. These reefs conform to the early stages in the classic Darwinian atoll model of fringing reefs surrounding a subsiding volcanic core. Growth is concentrated upward where the rate of reef growth keeps pace with the rate of substrate subsidence.

2.5.2 Sangkurang Archipelago

The Sangkurang Archipelago lies between latitude 4,20'-5,10'S and longitude 119,-119,25'E on a submerged plain which covers an area of some 16000 km². The gently shelving platform upon which the reefs grow is 50 km wide and 25-45 m. deep, and passes eastwards into the coastal plain of South Sulawesi (Fig. 16). Further east, the plain is bordered by a promontory of Tertiary limestones to the east of which lies the Sengkang Basinal Area (Section 3.4).

Prior to the late Pleistocene-Holocene transgression, the coastal plain including the platform upon which the reefs now grow, was emergent and suffered denudation. The present phase of reef growth in this area is postulated to have initiated after the last (Riss-Würm) interglacial i.e. 40,000-60,000 years ago.

The only reefs that might have existed earlier in the Archipelago are those at the outer western rim of the submerged plateau, bordering the Macassar Trench. These outer reefs form a discontinuous barrier reef ("toothed reef complex" of de Neve 1981) from Goseya in the south-west to Taka Bulango atoll in the north-west which drop off westwards into depths exceeding 1000 m. At least part of this interreef would have remained flooded prior to the onset of the postglacial transgression.

Average reef size, inter-reef spacing and water depth increase westwards away from the South Sulawesi coast. Reefs, especially unvegetated ones, are elongated in a north-south direction in response to prevailing currents, and reef growth is concentrated preferentially on the western and south-western flanks of islands, particularly around those islands that are close to the runoff from Sulawesi. Many rivers drain westwards from the Talaker-Pankajene plain bearing heavy sediment loads, and the closest islands to the Sulawesi coastline are 7 km.

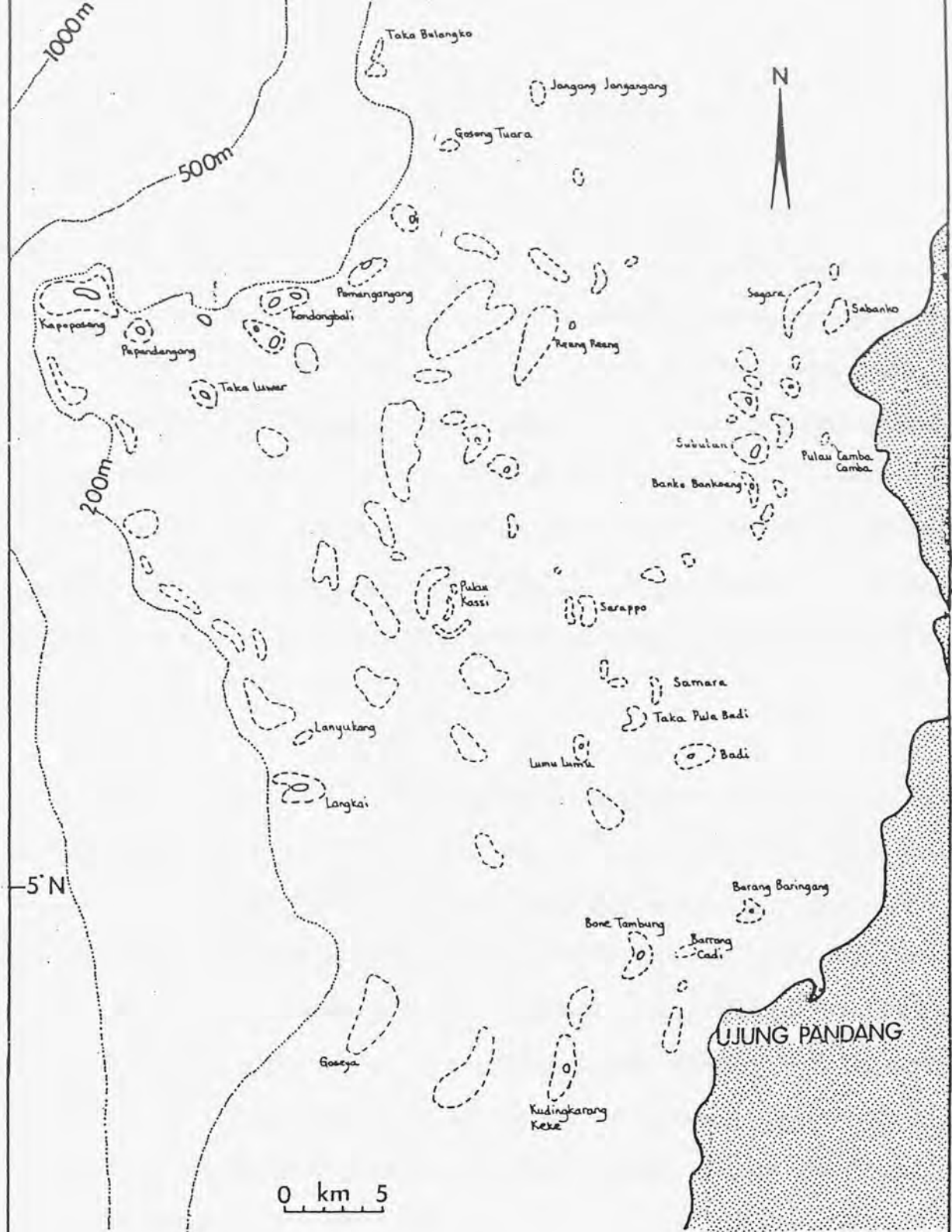


Figure 16 Map of the Sangkurang Archipelago, South Sulawesi

offshore e.g. Pulau Camba Camba. Islands are frequently concave to the west.

The patch reefs of the Sangkurang Archipeligo display a similar pattern of morphological zonation as that described from the Pulau Seribu (Section 2.3). Muddy algal-rich reef flats border some of the nearshore islands such as Pulau Camba Camba. The faunal and floral assemblage of these algal flats is dominated by Zostera, Sargassum and Turbinaria with common gorgonian sponges and rare boulder corals. The reef flat varies from 0.6-1 m. in depth and sediment contains upto 60% clay and silt much of which is terrestrially derived from the river draining into the Macassar Straits west of Pankajene. The fine sediment is anoxic 1 cm. below the surface and smells strongly of hydrogen sulphide.

Islands more distant from the Sulawesi coastline are relatively more exposed to the storms and currents that move northwards from the Flores Sea. Shallow reef flats are dominated by the sand flat environment described in Section 2.3.2(b) and sediments are coarse calcarenite, consistently negatively skewed and leptokurtic indicating a high degree of sorting. Ramparts bordering reef flats are less common than in the Pulau Seribu except around the outer barrier islands on the western margin of the Archipelago, suggesting that, overall, storm influence is weaker in this area. Where present, the ramparts border the western margin of the reef flat.

The coral diversity and percentage in situ coral cover are highest in the reefs most distant from the Sulawesi coastline. A wide terrace sloping from a depth of 11 m. to 16 m. is apparent along the reef bordering the western margin of Pulau Kondongbali - an outer barrier island. A sharp break in slope between the reef crest and wall is not present there. Elsewhere the reef slope has a gradient of between 30°-65° and is broken intermittently by gently sloping

ledges upon which reef detritus accumulates. These terraces and ledges may mark periods of temporary sea level stabilisation within the Quaternary time interval which has been dominated by transgression.

2.6 RECENT LITHOFACIES IN THE PULAU SERIBU

2.6.1 Introduction

It is evident from the study of Recent reefal environments, that lithofacies, communities and habitats are strongly related (Bathurst 1975). Research on the Pulau Seribu has resulted in the identification of four major subtidal and three minor intertidal-supratidal lithofacies, which reflect to varying degrees thirteen habitats and ten communities. The inter-relationships between lithofacies, habitats and communities and their distribution on Pulau Pari are illustrated in Figs 17-19.

A lithofacies is defined as an aerially restricted unit of sediment with lithological, structural and organic attributes which distinguish it from neighbouring units of sediment. The criteria used to define the facies are based on;

- (a) physical attributes of the sediment such as grain size, sorting, lateral and vertical variability, constituent composition and suites of sedimentary structures.
- (b) biogenic characteristics such as binding and bioturbation, and presence or absence of diagnostic organisms or faunal assemblages. The biotic characteristics of the environment are considered only where they exert an observable influence on the sediment and as a tool in predictive

Figure 17 - Distribution of habitats on Pulau Pari

	Intertidal swamp
	Beach
	Inter-subtidal sands
	Reef wall
	Thallophtyes
	Patch reefs and algae
	Supratidal terrestrial
	Coral fragment shoal
	Intertidal rampart
	Pelleted mud
	Unconsolidated avalanched debris
	Channel floor

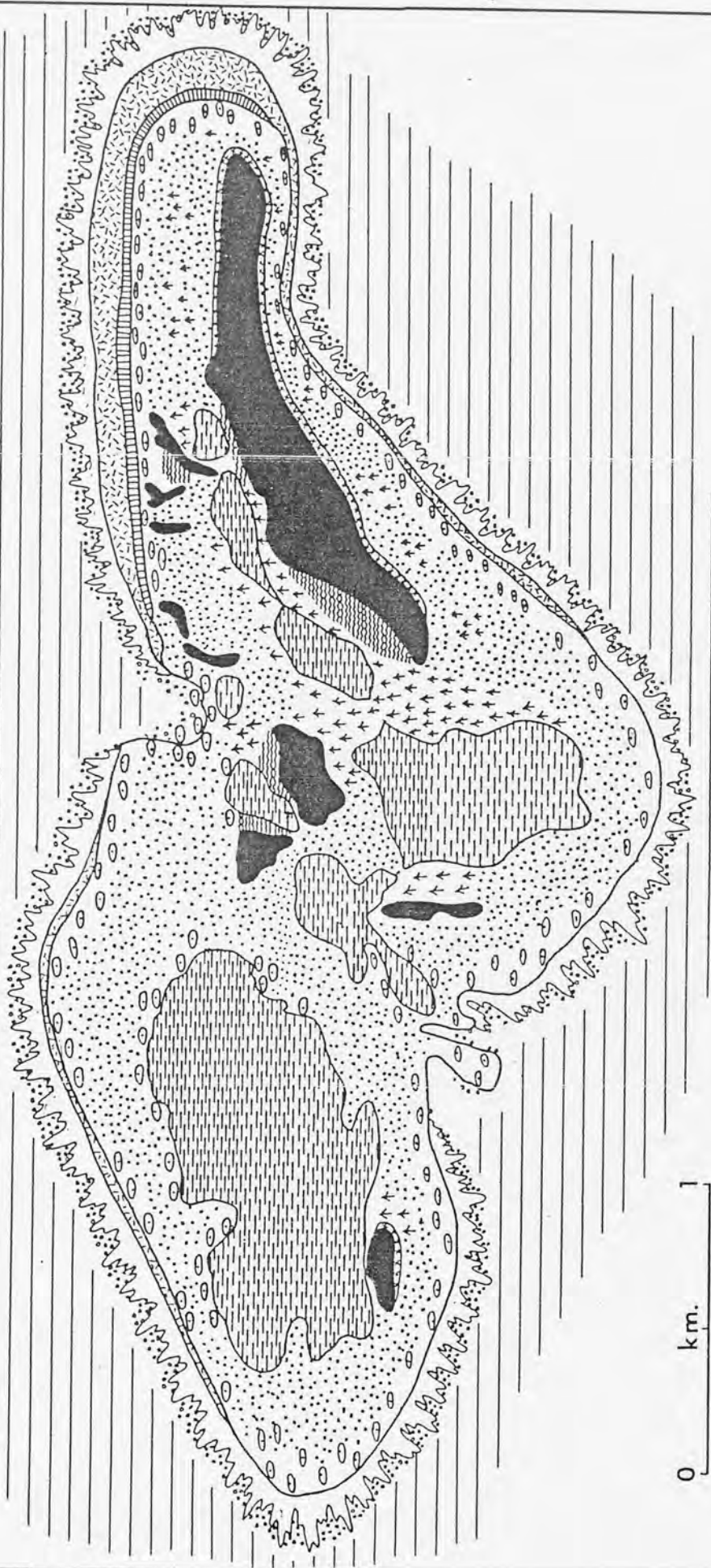












Figure 17 Distribution of habitats on Pulau Pari.

Figure 18 - Distribution of communities on Pulau Pari

-  Terrestrial
-  Mollusc-vagrant benthos
-  Callianassa-mollusc
-  Avicennia
-  Thalassia-mollusc-epibiont microfauna
-  Branched/foliose coral
-  Caulerpa - Halimeda
-  Montastrea - Caulerpa - Sargassum
-  Coral-gorgonian-alcyonarian
-  open channel foraminifera-mollusc.

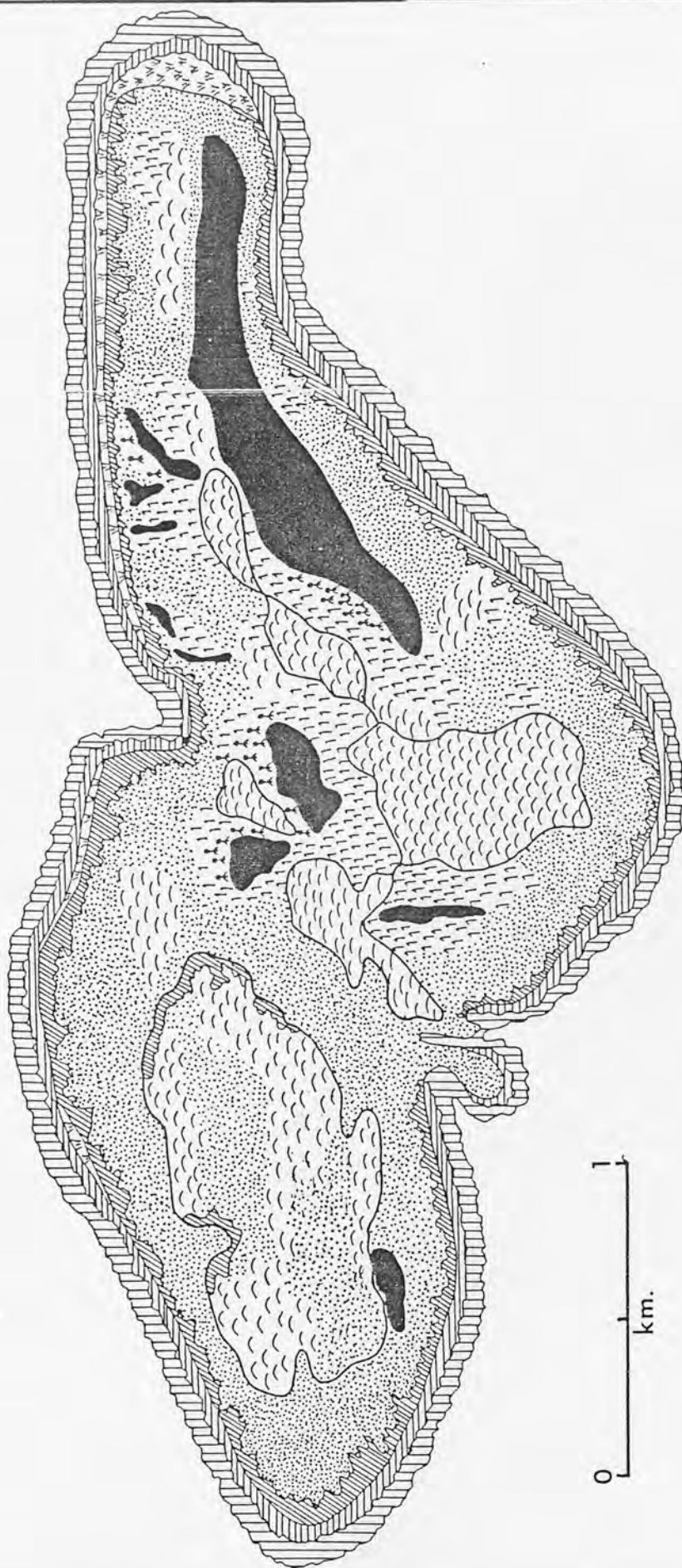









Figure 18 Distribution of communities on Pulau Pari.

Figure 19 - Distribution of Lithofacies on Pulau Pari

	Coral debris-coral-algal-mollusc	}	Coral-mollusc packstone-rudstone
	Coral-mollusc-skeletal		
	Coral cobble rudstone-grainstone		
	Sparsely bioclastic bioturbated pellet-mud		
	Winnowed coral-mollusc grainstone		
	Carbonaceous		
	Silty clay impure carbonate.		

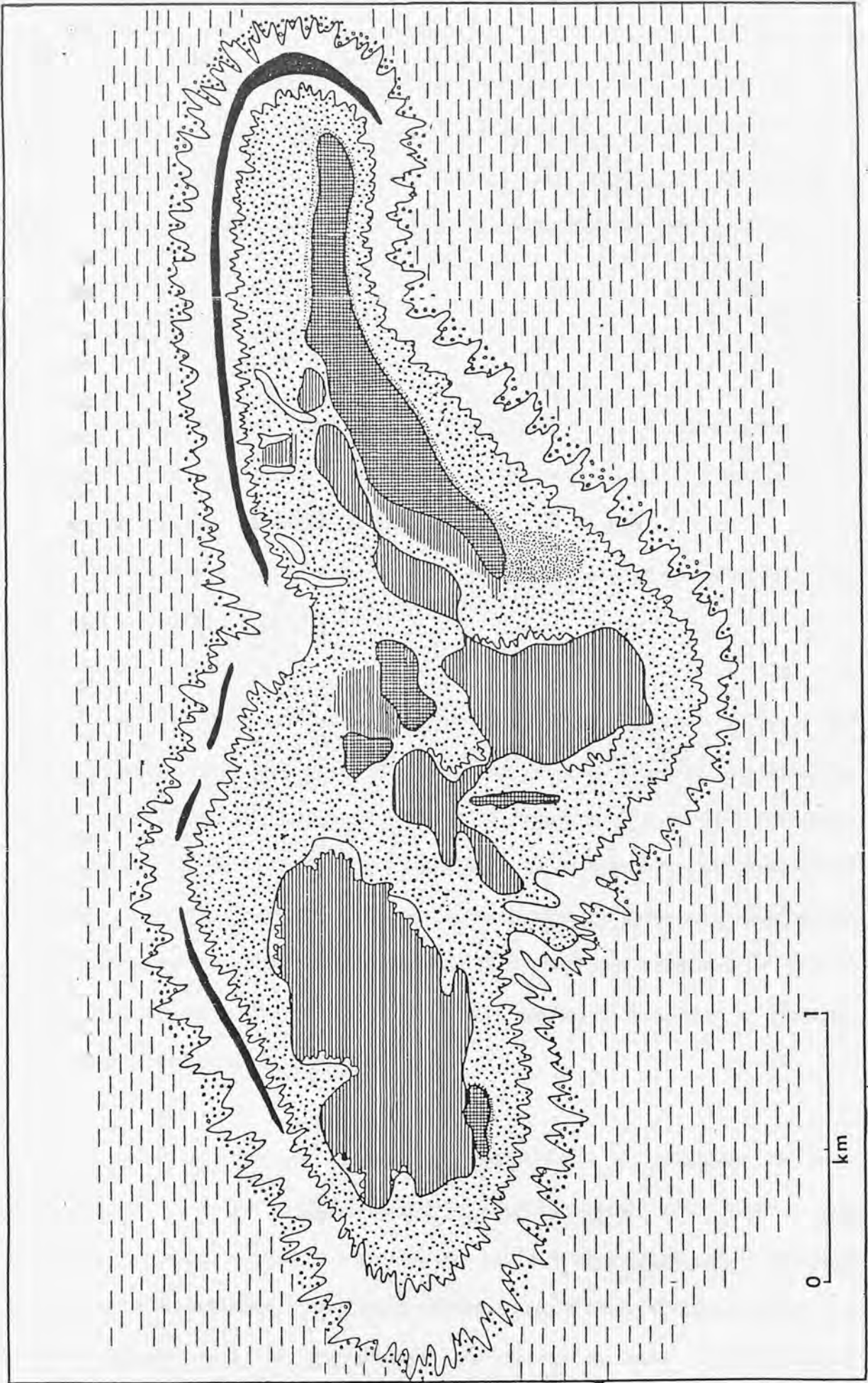


Figure 19 Distribution of lithofacies on Pulau Pari.

stratigraphy to characterise depositional environments. The community refers to the stable faunal and floral assemblage of an environment. Habitats are defined on criteria relating to depth, temperature and salinity, bottom topography, sedimentation rate, degree of exposure to waves and currents, relation to physiographic features such as the cay or reef edge, length of subaerial exposure and stability of the substrate.

2.6.2 Sediment Composition

The relationship between community-type and lithofacies was quantitatively investigated by studying the biotic contributions to the sediment in different facies (Swinchatt 1965). Twelve samples representing five environments were selected from the group of 200 samples gathered from the Pulau Seribu (Section 1.2).

Samples represented both relatively sheltered and exposed localities and each was broken into five grain size fractions prior to araldite impregnation. The results in Table 1 illustrate the degree of faunal control on different grain size fractions. Biotic contributions to sedimentation appear to be size-related (Flood et al. 1978). Study of the cumulative frequency grain size distribution graphs computed for 200 samples, reveals that most are composed of several straight-line segments which result from the mixing of a number of faunally controlled normal populations (Fig. 20).

Table 2 summarises the faunal composition of sediment in each environmental zone and includes data from Caribbean and Pacific reefs. Four components; corals, molluscs, foraminifera and the alga Halimeda, contribute the bulk of the sediment in the Pulau Seribu reef system. Coralline algae are virtually absent and the non-skeletal component in sand is very minor.

	SIZE CLASS	MEAN%	RANGE %	ST. DEV.	TREND
CORAL	GRAVEL	54.3	39.6 — 90	8.7	↓
	SAND coarse	49.8	31.7 — 69.6	4.6	
	medium	56.2	20.6 — 73.7	5.1	
	fine	53.8	33.6 — 70.5	5.3	
	v. fine	56.2	42.7 — 86.3	5.9	
MOLLUSC	GRAVEL	15.1	12.9 — 21.3	1.6	↑
	SAND coarse	12.4	5.6 — 21.3	3.8	
	medium	12.6	5.8 — 18.2	5.0	
	fine	9.1	3.1 — 16.8	2.8	
	v. fine	6.2	0.6 — 9.8	3.1	
ALGAE	GRAVEL	29.8	14.6 — 81.4	11.6	↑
	SAND coarse	30.5	6.3 — 43.1	7.2	
	medium	17.5	6.5 — 45.1	8.9	
	fine	20.	6.7 — 39.8	5.1	
	v. fine	18.3	4.9 — 40.	10.5	
PELLET	GRAVEL	1	0 — 3.5	1.0	↑
	SAND coarse	3.3	0 — 12.7	3.4	
	medium	3.0	1 — 11.6	2.9	
	fine	1.4	0 — 6.6	1.5	
	v. fine	0.03	0 — 3.4	0.9	
FORAMINIFER	GRAVEL	0	—	—	↓
	SAND coarse	0.6	0 — 3.6	0.4	
	medium	5.9	1 — 14.8	3.9	
	fine	6.2	0.6 — 12.	3.3	
	v. fine	2.3	0 — 8.2	2.0	

Table 1 Trends between grains size and component populations in the sand grade range.

Table 2 Faunal Composition of sediment in each environmental zone.

ENVIRONMENT GRAIN TYPE	CAY	INTER- TIDAL	LAGOON	REEF FLAT	CREST	REEF SLOPE	REEF BASE	TYPE 'A' CHANNEL	TYPE 'B' CHAN.	CAY (PACIFIC)	CAY (CARIB)	LAGOON (PACIFIC)	LAGOON (CARIB)	REEF FLAT (PACIFIC)
CORAL	59	46	26-51	58	50	53	63	72	9	9-45	9-31	15-42	4-28	15-36
MOLLUSC	33	29	30-39	13	10	10	9	21	18	6-33	2-20	9-18	7-18	12
FORAMINIFERA	1	6	1	5	3	4	2	3	12	16-51	1 18	2-29	3-7	10-23
CORALLINE ALGAE	—	1	1	1	2	1	—	—	—	9-47	10-27	6-61	1-21	23-52
GREEN ALGAE	—	11	—	18	27	28	17	1	—	2-14	1-60	1-77	1-61	2-10
ECHINODERM	1	1	1	2	2	1	2	2	3	2-10				
HOLOTHURIAN SCLERITE	—	1	2	1	2	1	3	1	1					
BRYOZOA	—	1	1	1	1	1	1	1	—					
PELLETS & NON- SKELETAL	—	2	5	2	1	1	1	1	—	1-3				
UNIDENTIFIED	7	6	—	3	2	4	2	—	1-20					
CLAY & SILT	1	—	12-20	2	—	0-2	1-4	0-4	16-57					

Miscellaneous components such as unconsolidated faecal remains, bryozoans, alcyonarian spicules and echinoderms are locally important but generally comprise less than 2% of the sediment.

Molluscs are more common than one might intuitively expect based on on-site population estimates which suggest that molluscs are relatively sparse compared to other carbonate producers. Their numerical abundance in the sediment may result from their ability to withstand comminution and abrasion. The relationship between standing crop and turnover time is also important.

Benthic foraminifera are relatively abundant compared with other Indo-Pacific reefs (Table 2) and in parts of Indonesia, foraminifera such as Amphistegina madegascariensis, Marginopora vertebralis and Calcarina spengleri assume a dominant role in the biomass of the reef system (Scrutton 1976). At Sanur Beach, south Bali, the foraminifer Baculogypsina comprises more than 95% of the sediment on intertidal beaches.

The small number of samples taken from each environment of deposition does not permit conclusions of statistical significance to be drawn regarding the degree to which environment may be inferred from quantitative grain composition data (Till 1970). However, despite the small sample population, the mean percentages reveal very clear trends suggesting that provenance may be estimated based on grain counts of samples from unknown localities.

Perhaps unexpectedly, the mean percentage of coral in the sand-fraction of the sediment decreases toward the crestal environment and reef slope which represent a peak in percentage cover of coral. This is an indirect result of the fact that algae, in particular the rapid-growing Halimeda, favour the same localities for growth, but the rate of production of sand-sized sediment from the

alga far exceeds that of coral. The cobble- and granule-grade sediment composition reflects the size of detached largely unabraded corals and algae, and the relative abundances of each are a function of proximal community structure. Coral breaks into large boulder-sized fragments and is the sole components of cobble-grade sediment, whilst the granule-grade sediment comprises approximately equal proportions of algae and corals except on sand falls where Halimeda predominates.

The percentage of algae in the sand-sized sediment follows an inverse trend to that of coral, peaking at the sites of highest biotic diversity. Brown et al. (1982) noted the incorporation of a coarse sediment fraction in outer reef flat sediments after the west monsoon and attributed this to the inability of the relatively weak wave energy between April and October to sort the sediment. The percentage of algae in the sediment exhibits a large standard deviation. This is a result of the variable wind and wave exposure at different localities of a single environmental zone which is reflected in both the percentage cover of algae, in particular Halimeda, and in the post-mortem winnowing of the sediment and removal or non-removal of other sediment constituents.

The percentage of Mollusca in the sediment decreases steadily seawards of the cay in inverse relation to water depth. Foraminifera follow a similar though slightly more obscure trend since their abundance in coarse sediment is constrained by skeletal size. A comprehensive survey of foraminiferal diversity was not undertaken, but from grain counts and microscopic study of samples, it is apparent that diversity follows a parallel trend with percentage abundance. Some of the more common micro-organisms collected from the reef flat environment are illustrated in Plate 24. Foraminifera are most abundant in the fine-medium sand grade which corresponds to the average test size of the unfragmented benthic species.

Bryozoan fragments and holothurian sclerites are more sporadic in occurrence and their abundance demonstrates no distinct trend in relation to environment. The percentage of faecal ^{unconsolidated} remains exhibits no relation to depth but visually increases in both directions away from the growing edge of the reef. This is a parallel trend to the areal percentage of unconsolidated sandy substrate available for burrowing and ingestion by grazing infauna (Fig. 12).

The results demonstrate that the relative abundances of vagrant benthic fauna such as Mollusca and foraminifera in different environments are well reflected in the sediment and that by contrast the relative abundances of sessile biota are less accurately reflected.

Lateral transport and vertical mixing may serve to blur the boundaries between physiographic zones. However, the above mentioned associations between community and lithofacies, strengthen the assumption that most of the sediment is produced very locally or in situ. The association between habitat and lithofacies is more tenuous, a single lithofacies being represented in widely separated habitats.

It is apparent from the results portrayed in Table 2 that a marked overlap exists between the intertidal and reef flat sediment samples, and the reef crest and reef slope. In the examination of ancient sediments, problems are likely to arise in the recognition of the two geomorphological zones which are effectively represented by only one lithological unit. By increasing the sophistication of description and broadening the scale of observations to consider the sedimentary unit in the context of laterally and vertically adjacent lithologies, the recognition of ancient sedimentary environments may become more specific. The following statistical treatment places emphasis on description of lithofacies

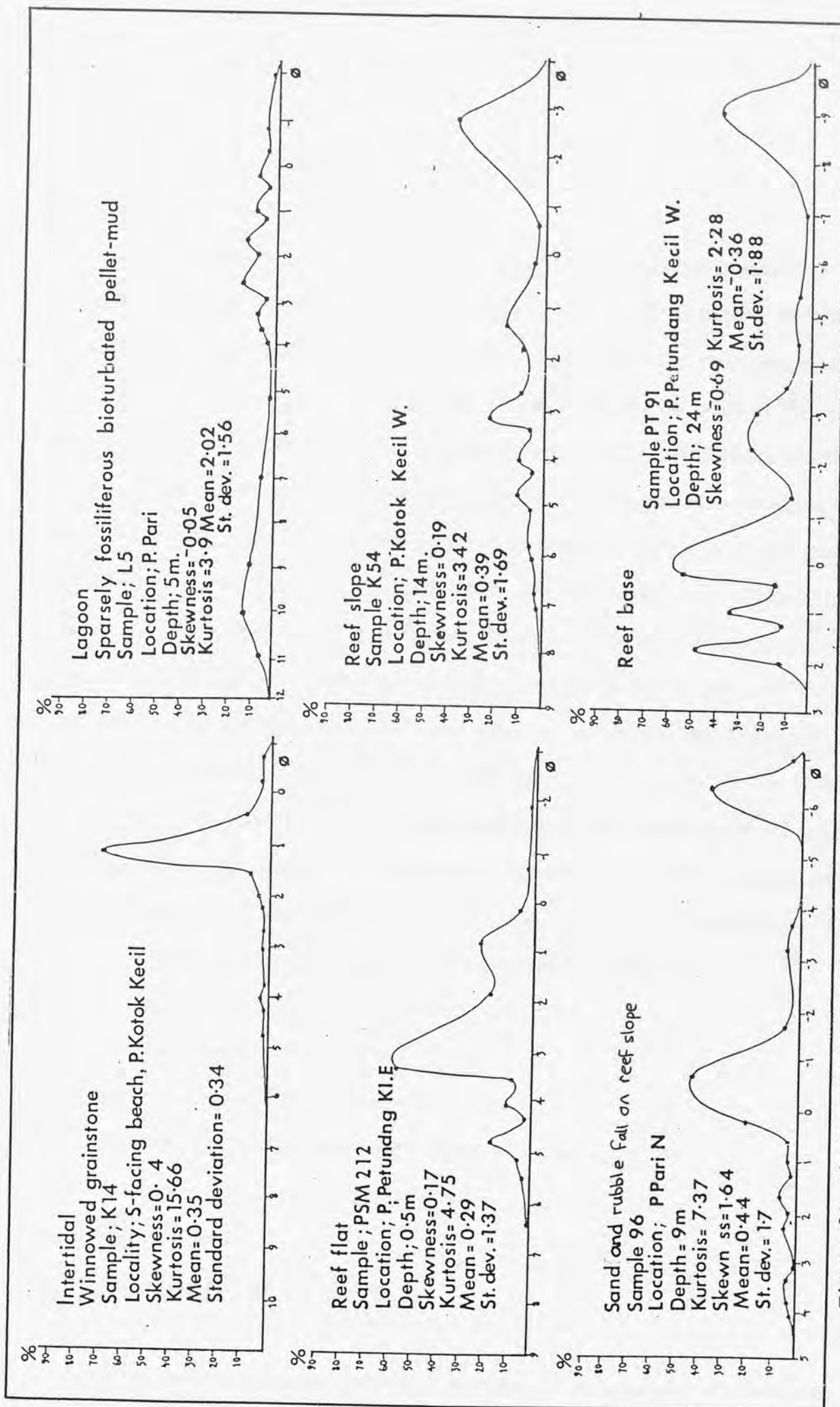


Figure 20 Characteristic grain size distributions related to environmental zones.

by grain size distributions.

2.6.3 Grain Size Distributions and Recent Lithofacies

Grain size distributions yield information which may be interpreted in terms of processes of sedimentation. Friedman (1961) used statistical methods based on grain size analysis to differentiate dune, beach and river sands and more recently El-Ella & Coleman (1985) demonstrated the validity of the technique in a provenance study of sediments from the Burdekin Delta, north-east Australia. However, carbonate grains are more heterogeneous in terms of shape and density than siliciclastic grains, and repeated analyses of the same samples yield less consistent results than are obtained from siliciclastic sediments of similar grain size (Griffiths 1967). Textural characteristics of carbonate sediments have been successfully employed by a number of authors (Clack & Mountjoy 1977; Brown & Dunne 1980) to aid in the interpretation of hydrodynamic regimes and so the sieve technique was adopted in this study bearing in mind its limitations. The weight percent of sand, gravel and mud were calculated from the grain size histograms derived from sieve analysis and triangular diagrams (Folk 1968) were constructed for each lithofacies (Fig. 21, Table 3). The lithofacies recognised in the Pulau Seribu reefs are;

- (a) coral-mollusc packstone-rudstone
- (b) coralgall packstone-grainstone
- (c) coral cobble rudstone-grainstone
- (d) sparsely bioclastic bioturbated pellet-mud
- (e) winnowed coral-mollusc grainstone
- (f) carbonaceous
- (g) silty-clay impure carbonate.

From the descriptive statistics derived from analysis of sediment

G = Gravel (>1mm) S = sand (62µm-1mm) M = mud-silt (<62µm)

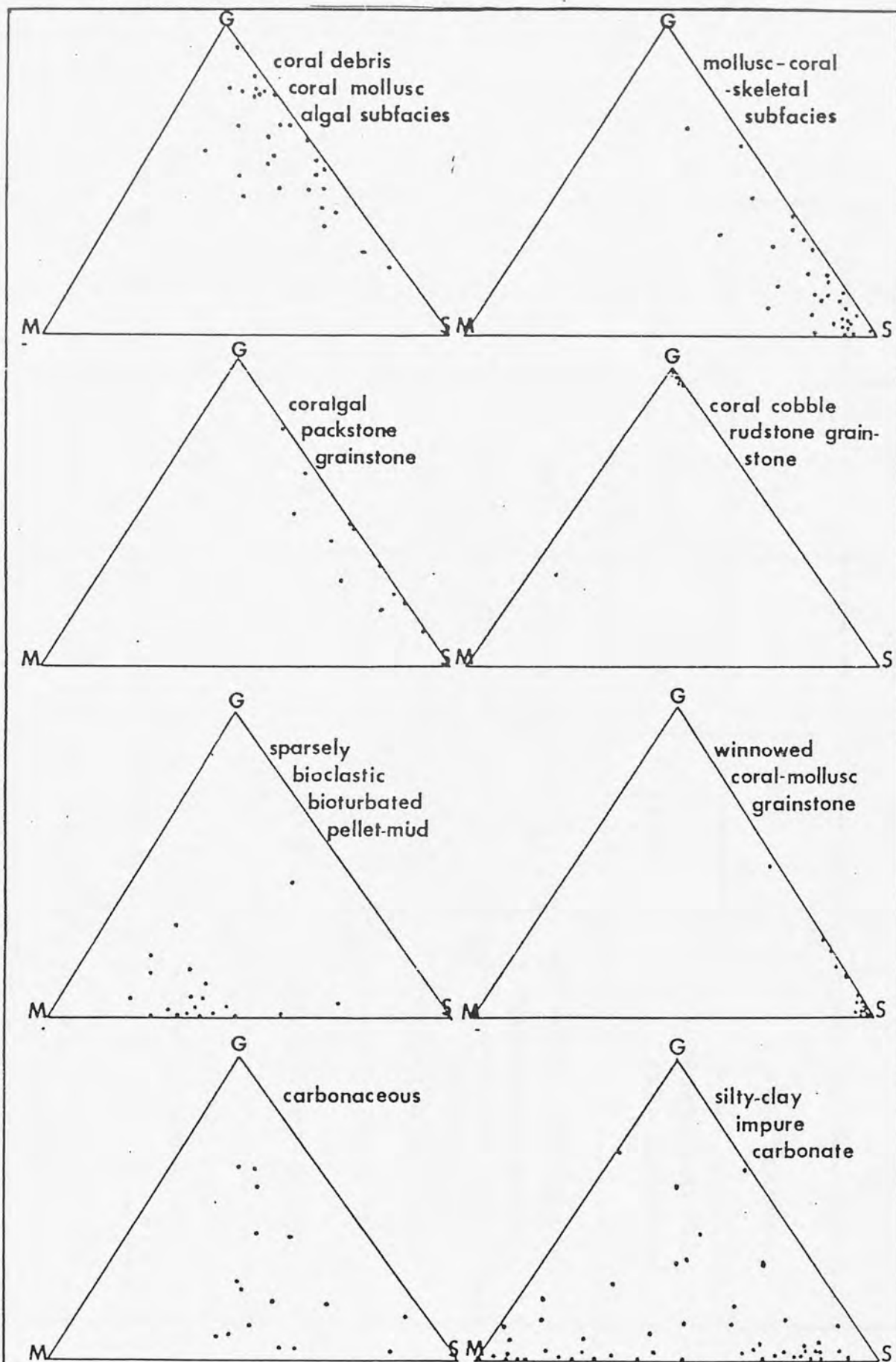


Figure 21. Triangular diagrams of Recent lithofacies of Pulau Seribu.

FACIES	GRAIN SIZE PARAMETER	MEAN (Ø)	STANDARD DEVIATION	SKEWNESS	KURTOSIS
CORAL DEBRIS - CORAL - MOLLUSC - ALGAL (47)		1.038	1.403	-0.009	3.908
MOLLUSC - CORAL-SKELETAL (60)		0.60	1.32	-0.451	4.02
CORALGAL PACKSTONE - GRAINSTONE (15)		1.158	0.728	-0.591	3.81
SPARSELY BIOCLASTIC BIOTURBATED PELLET-MUD (12)		3.2	1.61	0.01	3.1
WINNOWNED CORAL MOLLUSC GRAINSTONE (14)		1.486	0.821	0.52	8.73
CARBONACEOUS (6)		0.95	1.6	0.06	2.1
SILTY CLAY (39)		1.29	1.49	0.07	2.8

Table 3 Characteristic grain size statistics of Recent lithofacies in the Pulau Seribu.
(Numbers in brackets refer to numbers of samples used from each lithofacies).

textures, inferences may be made regarding source area. More significantly in the context of this study, likely post-burial textures may be inferred by assuming a logical sequence of diagenetic environments through which the depositional units might pass, and the likely response of the grains. The overall proportions of aragonite, high-magnesium calcite, low-magnesium calcite, and the microstructure of skeletal grains, are the principal factors governing the sediment reaction. The mineralogy of grain types composing the sediment is summarised in Table 4. The bulk mineralogy is a direct function of the faunal composition of the sediment. The non-organic mud fraction constitutes a very minor proportion of total sediment in reefal samples.

(a) Coral-mollusc packstone-rudstone lithofacies

The coral-mollusc rudstone- packstone facies is volumetrically the most important in the Pulau Seribu reefs, and represents six habitats which occupy four laterally adjacent reef zones (Figs. 17-19). Sediment is derived predominantly from the growing edge of the reef which is the crestal zone, upper reef wall and outer colonised moat. Sediment in the interstitial pockets within the upper reef slope and lagoon edge environments represents an in situ deposit, whilst that of the reef flat, lower reef slope, reef base and narrow channels is predominantly composed of transported sediment. Based on this major subdivision, two subfacies can be distinguished;

- (i) coral debris-coral-mollusc-algal subfacies,
- (ii) mollusc-coral-skeletal subfacies.

Whilst by definition, the content of the predominant allochemical components; corals and molluscs, are virtually indistinguishable in each of the subfacies, general trends in accessory biotic components and specific textural criteria typifying particular hydrologic regimes and communities, can be used to

TAXON	ARAGONITE	CALCITE Mol % Mg	BOTH ARAGONITE & CALCITE
		0 5 10 15 20 25 30 35	
CALCAREOUS ALGAE			
RED	R	X ————— X	
GREEN	X		
FORAMINIFERA			
BENTHIC	R	X ——— X ——— X	
PLANKTIC		X X	
SPONGES	R	X — X	
COELENTERATES			
MILLEPOROIDS	X		
SCLERACTINIAN	X		
ALCYONARIAN	R	X — X	
BRYOZOANS	R	X — X	R
BRACHIOPODS		X — X	
MOLLUSCS			
BIVALVES	X	X X	X
GASTROPODS	X	X X	X
SERPULIDS	X	X — X	X
ECHINODERMS		X ——— X	
ANTHROPODS		X — X	

X=common R=rare

Table 4 - Mineralogy of faunal and floral groups (after Scholle 1978)

infer subfacies and environment. In the following descriptions, those characteristics of the subfacies that are likely to be preserved in fossilised reefs are emphasised.

(i) **Coral debris-coral-mollusc-algal subfacies**

Overall, the internal texture of the coral debris-coral-mollusc-algal subfacies comprises disorganised nonsequential and unstratified units of packstone, wackestone, framestone, rudstone and floatstone. The subfacies represents an in situ deposit within the growing edge of the reef. Mud content is minor, coral diversity is high and algal detritus is abundant. The kurtosis of most samples is approximately 1.0 indicating a lack of sorting and winnowing of the sheltered sediment pockets. Exceptionally a kurtosis of 3.6 is recorded from algal gravel on the reef crest. Sediments are consistently negatively skewed, 75% of values falling between 0 - -0.2. The mean grain size is positive in most cases and the standard deviation of the mean is the highest recorded in all facies, averaging 2.4. Four samples collected from the upper reef slope have negative means ranging from -0.03 - -0.46.

The high proportion of cobble-sized debris is composed mainly of species of Acropora. The presence of a massive or branching framework between the pockets of sediment is clear indication of in situ growth. The preservation potential and ease of recognition of reef framework in buried sequences is dependent upon the energy of the environment which determines both the degree of framework destruction, and the texture of interstitial matrix. Jurgan (1981) described high and low energy reef margins from the Visayas, northern Philippines, and concluded that the relatively protected areas characterised by a branched coral community will be buried in an unsorted mud-rich matrix, in contrast to the winnowed interstitial sediment associated with outer-bank

exposed coral-algal dominated margins. Studies on the Funafuti and Bikini atoll cores however, indicate that reef framework is not always preserved (Section 3.2.8). Where it is present, palaeodepth of ancient reefs might be inferred on the basis of the main coral morphological types. As mentioned in Section 2.3.4, platy corals such as Acropora hyacinthus are often very common on the upper crest. Branched corals and occasional massive buttress-like colonies of Porites lutea dominate the lower crest and upper slope below which a mixed assemblage flourishes. Similar vertical sequences of coral morphologies have been described from Panama (MacIntyre & Glynn 1976), Curacao (Focke 1978) and Alacran (MacIntyre et al. 1977).

The highest percentages of boring macro-organisms colonise dead stable substrates around which circulation is good. With increase in depth, the availability of stable substrate relatively free of sediment cover is limited. Downslope there is also an overall gradation in texture from reef framestones into the floatstones of the forereef talus.

The percentage of mud present is a reflection of the degree of exposure of the sediment pocket to ocean swell and tidal currents. For this reason sediment from lagoon margin patch reefs is considerably muddier than that from outer reef edge sediments. Caution must be exercised in the interpretation of ancient reef edge sediments, however, since muddy sands are also found to accumulate in the sheltered low energy microenvironment of leeward reef edge cavities. In ancient sediments it is frequently difficult to differentiate between primary and diagenetically-derived mud and mud derived from the breakdown of algal colonies (Wolf 1965). Where found, the mud contained in the reef slope and crest sediments was composed of aragonite and calcite with minor quartz and trace amounts of smectite, illite and kaolinite. That in lagoon edge sediments was exclusively carbonate.

The presence of fibrous aragonite or micritic high-Mg calcite cements within the partially sedimented cavities (Section 2.4.2) is evidence of considerable internal circulation of water in a relatively exposed location (Marshall & Davies 1981).. In vertical section the lagoon margin sediments might also be distinguished from those of the reef edge on the basis of the facies sequence. Lagoon margin coral-mollusc wackstones will be interlayered with coral-mollusc packstones of the reef flat and the distinctive sparsely fossiliferous bioturbated pellet-mud facies of the lagoon bottom.

(ii) **Coral-mollusc-skeletal subfacies**

This subfacies represents the reef top environment - an area of negligible in situ growth. Most of the reef top is subjected to continuous agitation, so that the sediments are virtually mud-free. Since the subfacies comprises transported sediment, the grains are more fragmented and range from moderately well-sorted sand flat sediment to unsorted sediments within the baffle zones of algal flats. This is reflected in the kurtosis values which are close to 1.0. The maximum kurtosis value recorded is 2.38 for the biogenically-sorted upper layer of sediment burrowed by Callianassa. Skewness is slightly to moderately negative in all samples 25% of values being less than -0.25 and 75% less than 0. Mean and standard deviation of the mean values are similar to those of the coral debris-coral-mollusc-algal subfacies reflecting the diverse range of microenvironments represented by this lithofacies.

The range and overall percentage of accessory organisms is relatively high compared to the coral debris-coral-mollusc-algal subfacies since the high areal percentage of unconsolidated sand supports a diverse infauna. High benthic foraminiferal diversity reflects proximity to the reef float and the percentage of

epibiont foraminifera such as Sorites sp. and encrusting serpulids reflects the availability of thallophytic substrates. Calcareous cyanophytic algae, whose distribution is closely related to wave energy, are concentrated on exposed reef edges but are conspicuously absent in lagoon edge and reef flat habitats. Sedimentary structures are rarely preserved because of bioturbation, mainly by crustaceans.

(b) Coralgal packstone-grainstone lithofacies

The coralgal packstone-grainstone lithofacies is rather localised in its distribution occurring in some of the highest energy locations around the margins of patch reefs. The sediment occurs in well-defined chute-like to irregular talus fans which avalanche down the slope (Section 2.3.5.b). The most distinctive characteristic of the facies is the extremely high percentage of Halimeda gravel (Table 2, Fig. 21e). Coral is of secondary volumetric importance and other constituents are very minor. In plan, the facies geometry of sand and rubble falls exhibits a cross-cutting relationship with other facies and environments, being orientated perpendicular to the reef edge. In vertical sequence it might be expected that the sandfalls would be encountered interlayered with coral-mollusc packstones and coral framestones of the reef slope and reef crest. Internal cementation within Halimeda grains (Alexandersson & Milliman 1981) produces a sediment relatively resistant to breakdown and whose characteristics are likely to be preserved. In the absence of this it is likely, with time, that mechanical or biological disintegration of the plates to aragonite spicules (Wolf 1965) or mud would result in a shift of the mean grain size toward the mud grade and the production of a bimodal or poorly sorted muddy coral packstone sediment. The present sand size porosity is thus not preserved and it would be difficult to distinguish this facies from the coral-mollusc packstone-rudstone facies.

(c) Coral cobble rudstone-grainstone lithofacies

Coarse accumulation of coral debris are dumped on the margins of the table-flat reef top where shoaling waves lose the ability to transport cobble-sized fragments. The shingle rampart environment represented by the coral cobble rudstone-grainstone facies is volumetrically very minor but is particularly interesting in that it is the only facies to prograde cayward, in opposition to the outward progradation of all other facies (Fig. 10). Presumably there is a maximum width of the outer submerged shingle zone (Section 2.3.4) beyond which shoaling waves can no longer maintain the steep cayward slip face of the emergent shingle rampart.

On the living reef, the lithology is distinctive through its exceptionally high content of very coarse sediment, almost all of which is less than -2ϕ . Grain size analyses were not undertaken for this facies due to the practical difficulties involved in sampling and transporting the coarse bulky sediment (Plate 12d). From inspection however, it is clear that mean grain size increases cayward from approximately 0ϕ in the subtidal portion to $-2 - -8\phi$ in the supratidal-intertidal portion (Section 2.3.4).

Textural characteristics of the facies are related to the particle size gradient. The subtidal shingle is relatively more rounded and winnowed than the supratidal boulders, and is stabilised by a mat of algae (Plate 12a). The cavernous interstitial pore network of the supratidal portion of the coral cobble rudstone-grainstone facies is infilled with poorly sorted coarse coral-Halimeda sediment and live binding algae are minor with the exception of rare encrustations of rhodophytic algae.

In vertical section, the facies coarsens upward representing the buildup of

rubble from a subtidal shingle zone to a supratidal rampart. Since the facies gradually advances seaward over the outer reef flat (Plate 12b), it might be expected in a vertical transgressive sequence to find the coral debris-coral-algal-mollusc subfacies of the outer colonised moat, infilled and overlain by the coral cobble rudstone-grainstone facies. In ancient examples however, difficulty is liable to be experienced in distinction of coral cobble rudstone-grainstones from coral framework of the reef core.

(d) Sparsely bioclastic bioturbated pellet mud lithofacies

Fine grained carbonate sediments accumulate in sheltered areas on the reef platform well away from the main loci of carbonate production. The main environment represented by the sparsely bioclastic bioturbated pellet-mud facies is the lagoon bottom although the facies is also encountered rarely along protected intertidal mangrove-colonised flats and shorelines oblique to wave action. The facies reflects a lack of wave exposure or current disturbance and is consequently only found accumulating on the extensive reef platforms which are restricted to the southern part of the Pulau Seribu group (Section 2.3.3).

Texturally the sediments are unimodal and leptokurtic being composed predominantly (between 11 and 42%) of lime mud. Skewness values are low, ranging between -0.18 and 0.22, whilst the standard deviation of the mean is low in the centre of the lagoon and increases towards the margins. The sediment fraction greater than -0.5ϕ is composed predominantly of lime mud aggregates which are interpreted to be derived from the fragmentation of faecal pellets produced by gastropods, arthropods, polychaetes and fish. The sediment is thoroughly bioturbated by burrowing infauna and algal micritisation of scattered skeletal grains is important and makes grain identification difficult. The sediment-water content of mud substrata is very high (up to 90%, Rhoads 1973)

and the fluidity of the sediment limits epifaunal colonisation. The characteristic organisms inhabiting lagoon bottoms are those that live on or in unstable muds as burrowers and grazers, the most conspicuous members being gastropods, algae and crustacea. The composition of skeletal grains from this facies poorly reflects the nature of the community since most of the crustacea and polychaetes in particular, disintegrate after death. Important sediment contributors are restricted to the lagoonal environment, and are algae and a variable amount of coral debris relating to the proximity of lagoon edge patch reefs.

The composition of the mud fraction further assists in distinguishing samples from lagoons and intertidal mud flats belonging to this facies. Intertidal muds contain a higher percentage of organic matter and insolubles than lagoonal muds. Distinctive sedimentary structures likely to be preserved in the former include gas bubbles (Cloud 1960), and evidence of vertical mangrove prop roots. X-ray diffraction shows that the composition of lagoon muds is pure carbonate comprising a mixture of aragonite and calcite. Presumably the mud is derived from mechanical and biological breakdown of corals, algal disintegration and comminuted skeletal material from pelagic organisms.

The presence of burrowing Callianassa in both environments results in biogenic sorting of the upper levels of the sediment (Section 2.3.2b) and the coarse shell-lag lining to burrow entrances may be preserved unless destroyed by subsequent biogenic reworking.

(e) Winnowed coral-mollusc grainstone lithofacies

The winnowed coral-mollusc grainstone lithofacies accumulates in narrow intertidal shorelines and small offshore intertidal spits and bars. Volumetrically

this represents a very small part of the total reef volume, but its textural characteristics and the sedimentologically and possibly diagenetically important zone it represents justify separate discussion.

The sediment consists of well to very highly sorted coral-molluscan sands devoid of mud, with corals and molluscs being present in approximately equal abundance. The kurtosis of these sediments ranges from 0.79 - 4.05 and is the highest encountered on the reef. The most leptokurtic samples are encountered on south-facing beaches on moderately agitated shores where the reef flat is narrow. Sediment is variably skewed from -0.31 - 0.57 and the mean grain size is directly related to the energy of the beach, ranging from 3.12 ϕ on sheltered beaches to 0.57 ϕ for relatively exposed intertidal sands.

The sediments are generally highly bioturbated by gastropods but elsewhere display flat reefward inclined lamination.. Uncemented, relatively coarse, biomodally sorted segregations also occur, as a result of high tide events and storm sedimentation (Plate 4b). These berms are composed of very coarse sand and shingle-sized coral fragments, whole gastropods and disarticulated but unfragmented bivalves. In vertical upward-shallowing sequence this facies grades up into the carbonaceous lithofacies through a transitional zone of moderately to poorly sorted rootletted impure coral-mollusc packstone.

Emergent reefrock is apparent on the south of Pari cay (Plate 22a) west of Pulau Melintung, and used to be visible on the south-east beach of Kotok Kecil (Plate 22b). Sometime between November 1984 and June 1985 the inner reef flat and beach on Kotok Kecil was artificially built up and reinforced with blocks of blasted coral by the new owners of this island, and the reefrock is now obscured. Where found, the reefrock forms small ledges close

to the water's edge, approximately 6 cm. above the sand level. Shoreward the rock is buried beneath upper intertidal sands, and is coincident with the water table. The reefrock has a honeycombed appearance and is riddled with cavities 1-6 cm. in diameter (Plate 22c). Branched massive and solitary corals and occasional molluscs are cemented in a coarse sand matrix. The fragments are highly bored and bioerosion is clearly active at the present day since living attached molluscs are prolific. The original pore structure of the coral is considerably solution-enlarged. The rock is composed almost entirely of whole in situ colonies rather than unconsolidated debris. The most prevalent corals are Porites, branched Acropora and platy and flabellate species. Debris among the colonies is mainly composed of Acropora branches and articulated molluscs (Plate 22d). Its existence is evidence that an area of former active growth has been either tectonically elevated, or that the sealevel has since dropped slightly.

(f) Carbonaceous lithofacies

The carbonaceous facies is an impure carbonate accumulation with a high organic carbon content, resulting from the establishment of a mixed terrestrial floral community on supratidal portions of the reef. The average grain size falls within the medium-coarse sand grade and the sediment is slightly negatively skewed. Sorting is moderate to poor, kurtosis average 1.0. Textural and compositional characteristics such as rootletting and the presence of terrestrial fauna and wood fragments clearly distinguish the facies from subtidal and intertidal lithologies. The tripartite stratification of the sediment is depicted in Fig. 7. Downwards the carbonaceous facies grades into the leptokurtic winnowed grainstone facies or the fine-grained and rootletted sparsely bioclastic bioturbated pellet-mud facies.

The presence of a freshwater lens such as is encountered on most islands within the carbonaceous facies, should produce clear diagenetic textural effects such as meniscus and blocky low-Mg calcite cements and dissolution vugs. Due to the presently unlithified nature of the sediment, however, the visible effects of dissolution and early cementation might be largely eradicated through compaction.

The grains comprising the sediment have mixed provenience; the carbonate fraction is derived from the reef flat, whilst the insoluble fraction is largely locally derived from postmortem biodegradation of the organic community. The ultimate fate of the carbonaceous facies is largely dependent on temperature and depth of burial, which determine maturation of hydrocarbons or peatification and the formation of coal.

(g) Silty-clay impure carbonate lithofacies

Fine-grained carbonate and non-carbonate mixtures accumulate in off-reef channels in an environment which is below wave-base but affected by the biannually reversing monsoonal currents. Sediments in narrow type a channels (Section 2.3.7), and in close proximity to the reef in type b channels have a platykurtic grain size distribution and are slightly negatively or zero-skewed. By contrast kurtosis values of upto 5.0 and positive skewness values between 0.208 and 0.403 are recorded for distal type b channel samples. The ϕ value of mean grain size increases with distance from reef base ~~as does~~ the standard deviation of the mean (Fig. 22).

The sources of sediment are three-fold:

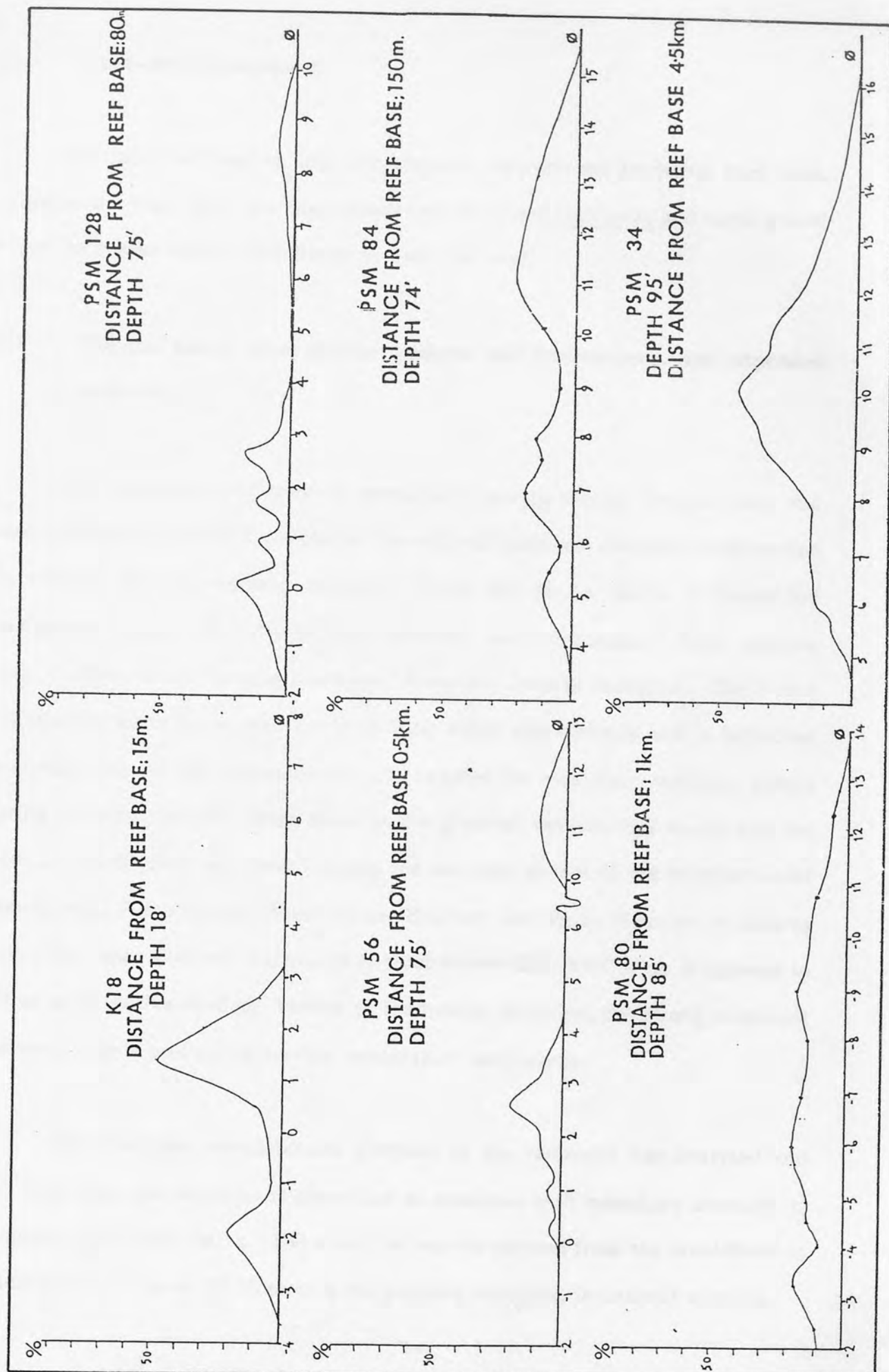


Figure 22. Changes in grain-size profiles related to distance from reef base.

(i) **Reef-derived sediment.**

Sediment encroaches into the channel environment from the reef base. Close to the reef there is a high proportion of coarse Halimeda and coral gravel which decreases rapidly with distance from the reef.

(ii) **Planktic fauna, open marine molluscs and foraminifera, and suspended sediment.**

The suspended sediment is presumably partly locally derived from the reef, and partly derived from fluvial run-off, off-platform sediment resuspended by storms, and atmospheric fall-out. From the air, a plume of suspended terrigenous largely fluvially-derived sediment and contaminant from onshore Java is often visible moving northward from the Jakarta coastline. The plume migrates in accordance with the prevailing winds and currents and is deflected westward toward the Sunda Strait. It reaches its maximum northern extent during the east monsoon when there is the greatest amount of run-off, and the most affected reefs are those fringing the southern shores of the southern-most islands, e.g. Pulau Damar Besar, Pulau Bidadari and Pulau Nyamok in Jakarta Bay. The Inner Channel orientated approximately ESE-WNW (Fig. 3) appears to act as an effective southern barrier to freshwater pollution, the strong east-west currents largely preventing further penetration northwards.

The insoluble non-carbonate fraction of the sediment was analysed and the main clay species present identified as smectite with subsidiary amounts of kaolinite, illite and quartz. The smectite may be derived from the breakdown of volcanic clays. Figure 23 illustrates the percent insolubles in channel samples.

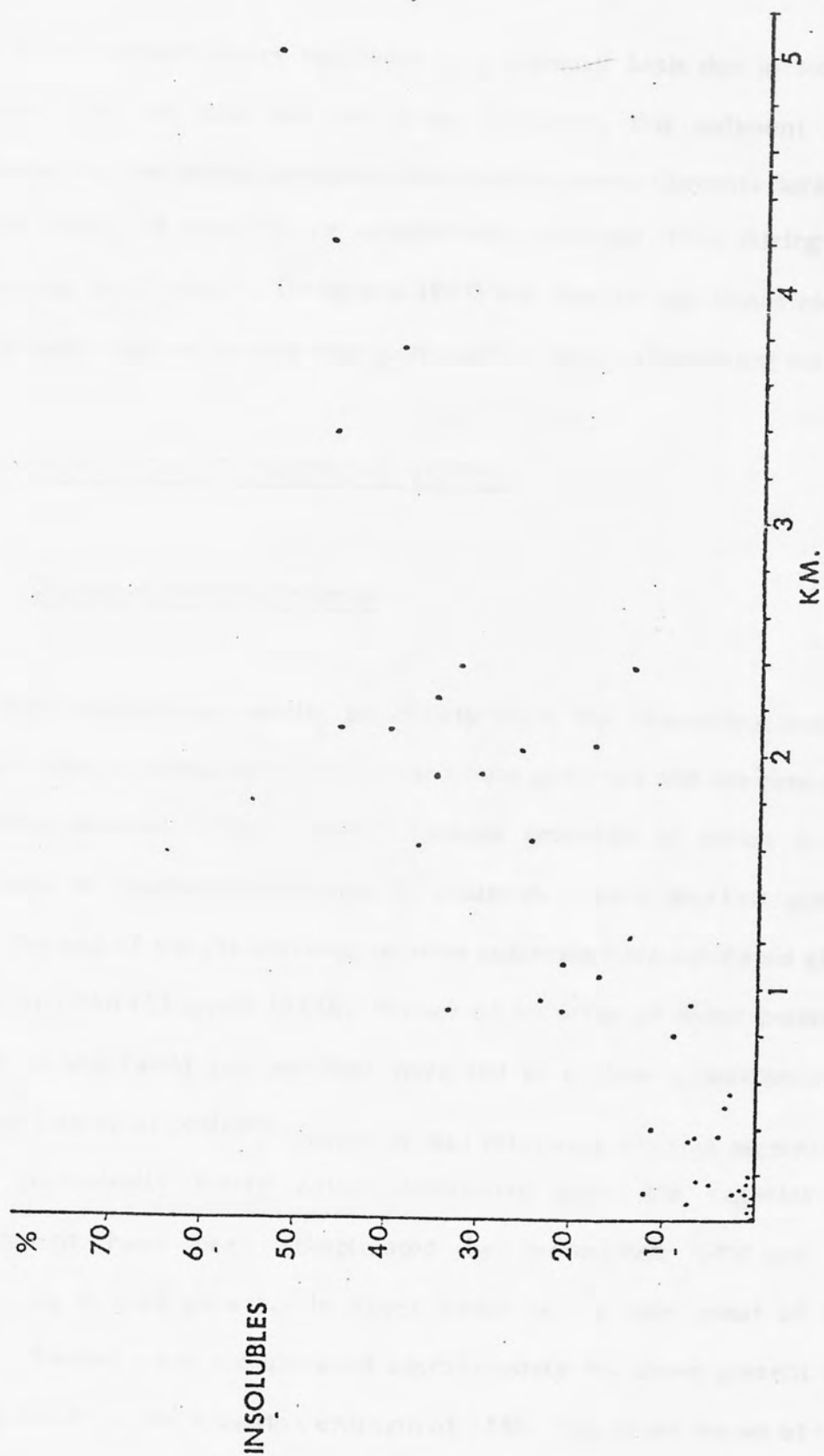


Figure 23. Relation between percentage insolubles and distance from reef base.

- (iii) **Sediment moved along the seabed from laterally adjacent areas.**

This sediment source oscillates on a biannual basis due to the reversing monsoon. At the edge of the Seribu Platform, this sediment moves off downslope into the basins and out of the reefal system. Currents during the east monsoon (upto 28 cm.s^{-1}) are considerably stronger than during the west monsoon (up to 17 cm.s^{-1} , Umbgrove 1947) and may be significant especially in the relatively shallow, narrow type a channels in terms of sediment movement.

2.7 EVOLUTION OF THE PULAU SERIBU

2.7.1 Change in Relative Sealevel

Reef morphology results principally from the interaction between the accretion rate of corals and detrital carbonate sediment and the rate of change in relative sealevel. The three-dimensional geometry of facies is primarily determined by Quaternary changes in sealevel. Since the last glacial peak toward the end of the Pleistocene, relative sealevels have oscillated globally by more than 100m (Chappell 1983). Studies of an array of dated palaeosealevel markers in the Great Barrier Reef have led to a close understanding of the Holocene history of sealevel change in that relatively inactive tectonic setting. In the tectonically highly active Indonesian area, the vagaries of reef establishment have been complicated by pronounced localised tectonic disturbances to reef growth. In Anyer Kedul on the west coast of Java, for example, Recent reefs are elevated approximately 4m above present sealevel. This is a result of the Krakatoa eruption of 1884. The broad trends of Holocene sealevel movement are of global extent however, difference in the precise timing and in the amplitude of fluctuations caused by local tectonically-induced pulses of basement movement are likely. In the northern Great Barrier Reef, a

glacio-eustatic transgression occurred from the end of the Pleistocene until approximately 5000 B.P. A gradual regression took place after 2000 B.P. in response to the later dominant effect of hydro-isostatic crustal readjustment.

Batchelor (1979) documented discontinuously rising last Cainozoic sealevels in south-east Asia. Such intermittent changes after the Pleistocene glacial event can account for the construction of a number of submerged wave-cut terraces reported (Cook 1982) to occur at a depth of 4m at Pulau Madaum reef (west flank), Pulau Sekati (west flank), Krangbalik-layer and Gosong Cungka (north flank). These are related to the period prior to the latest sealevel rise. The restriction of terraces to these islands results from the inevitable blurring of submerged topography resulting from overgrowth by large irregularly-shaped coral colonies. Raised reef rocks in the Pulau Seribu (Section 2.6.3e, Plate 22), dating from a period of higher than present relative sealevels, are elevated a maximum of 40-70cm above present low tide level, compared to a maximum difference of 4.9m in Australia. This suggests that, in comparison with Australia, the maximum late Holocene sealevels for the west Java Sea area were lower or the peak was achieved rather more recently.

2.7.2 Model for Reef Growth in the Pulau Seribu

(a) Initiation

The precise controls on the loci of reef growth are unknown but dunes, beach bars, delta lobes or fluvial overbank deposits related to the Pleistocene drainage system (Section 2.2.2) provided solid elevated substrates for initial colonisation. This drainage system had a longer term effect on inter-reef spacing and the distribution of type b channels (Section 2.3.7) which, in the south of the Pulau Seribu, are considered to be inherited from former river valleys.

The influence of a palaeodrainage system in controlling the loci of subsequent reef development has been described from Belize (Choi & Ginsburg 1982), where reefs can be seen to have grown up on the elevated portions of an alluvial landscape.

The influence of Pleistocene reef limestone as a control on Holocene reef development has been proven in Australia. Cores through the Great Barrier Reef and elsewhere (Davies 1983b) indicate that the present phase of Holocene reef growth represents a relatively thin capping on pre-Holocene reef limestones and that present reef form is strongly governed by the configuration of the underlying karstified limestone. Discontinuity surfaces marking a major hiatus in reef growth during glacial regression have been encountered worldwide at depths of 9-100m (Stoddart *et al.* 1978). In the Pulau Seribu, in the absence of seismic transects or direct core data for the Seribu Platform, it is not possible to assess the extent or presence of inherited substrate.

There is considerable variation worldwide in calculations of Holocene and Recent coral reef growth rates. Reported values range from 0.2-6m. 1000 yrs⁻¹ in the Great Barrier Reef and 0.38-4.85m. 1000 yrs⁻¹ in Floridan reefs (Davies 1983b), to 8-15m. 1000 yrs⁻¹ in Caribbean reefs (Adey 1978). At One Tree Reef (Australian Great Barrier Reef) and Pacific Panama, where measurements have been made both of Present and Early Holocene growth rates, there is a deceleration in the rate of growth over this time period. The most rapid rate of Holocene sealevel rise recorded in the Great Barrier Reef between 8000 B.P. and 6000 B.P. is 10m. 1000 yrs⁻¹ (Thom & Chappell 1978, McLean *et al.* 1978). Adey (1978) suggested that growth rates in a moderately low energy acroporid-dominated environment - such as the Pulau Seribu - where a porous open framework is constructed, is higher than in a comparatively wave resistant compact structure characteristic of high energy conditions. Taking a growth

rate of 8-15m. 1000 yrs⁻¹ suggested by Adey, it is possible to create the presently observed thickness of 30-35m during the Holocene transgression. Thus, although the existence of an underlying pre-Holocene reefal structure cannot be dismissed, it is quite likely that the Pulau Seribu are entirely Holocene in age. In support of this, there are no exposed or subtidal Pleistocene limestone ledges in the Pulau Seribu, evidence of which is found in all other areas of reef growth where pre-Holocene limestone underlies present growth.

Studies of reef nucleation, particularly in the Great Barrier Reef (Davies 1983a) indicate that there is a lag between flooding of the foundation in which present reefs are rooted, and colonisation. Assuming that reef initiation did not occur until some time after the transgression was underway, initial accretion would occur at the maximum rate with coral growth unconstrained by sealevel. On reaching the level of low tide further upward growth is only possible as long as relative sealevel continues to rise. Under conditions where relative sealevel rise is less than the potential rate of coral growth, the early exclusively upward growth would change to combined vertical and lateral expansion. The initial vertical growth would result in a pillar-like structure of reef framework and late upward and lateral growth constrained below m.l.w.s. would result in an extensive shallow dish-like structure. As Fig. 24 illustrates, the volumetric importance of reef top facies relative to the reef framework is dependent on the rate of reef growth relative to the rate of sealevel rise. The relative change in sealevel is the sum of eustatic change and subsidence. If these rates are approximately equal, the growing reef will be continuously accreting vertically and the entire reef body will be composed of framework facies or their diagenetically modified decendents (Fig. 25b). If potential reef growth rate exceeds the rate of sealevel rise however, then having reached sealevel, lateral accretion at reef margins will predominate. Under such circumstances reef top facies will develop relatively early in the evolution and constitute an important

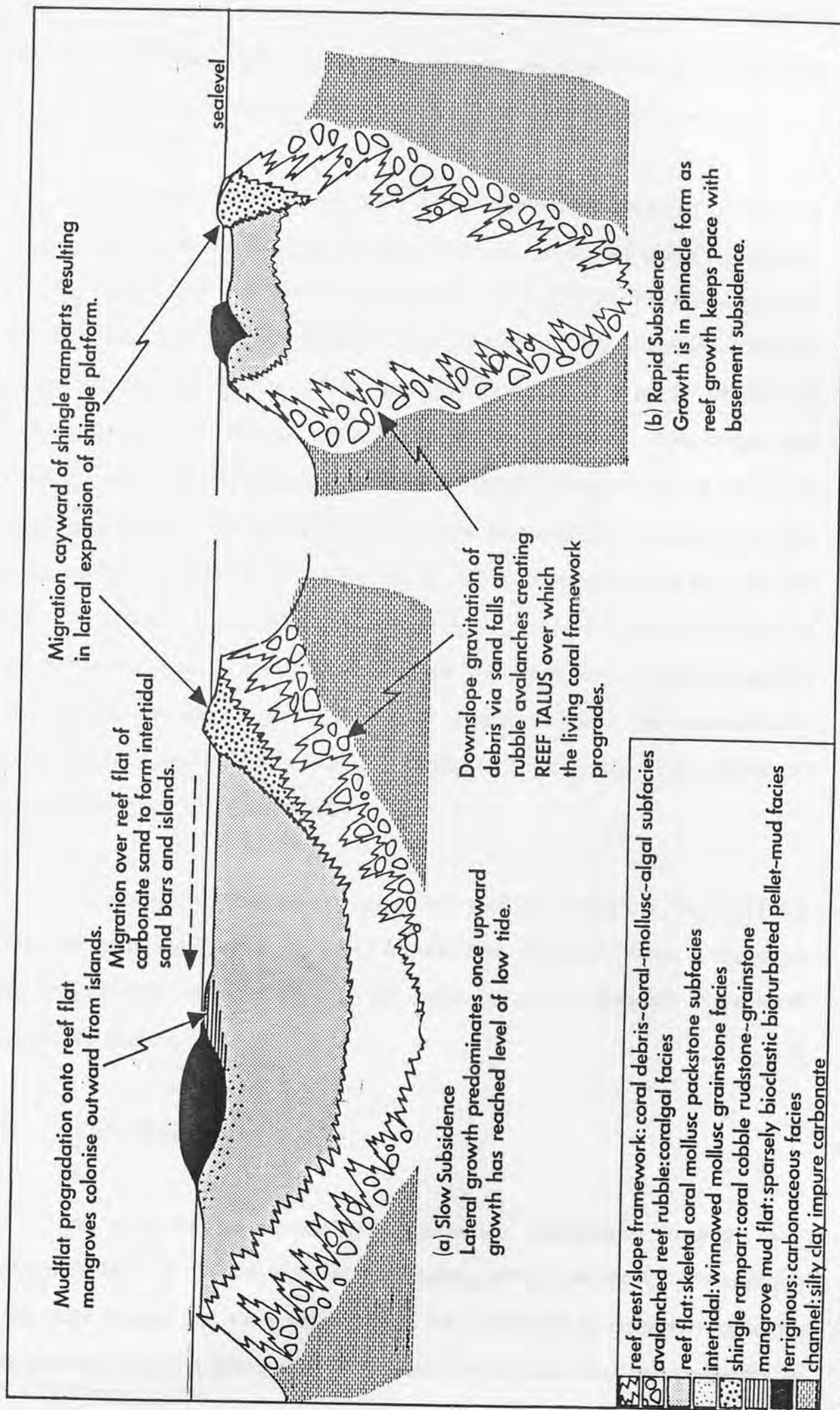


Figure 24 - Hypothetical model of northern- and southern-type reef growth.

fraction of the bulk reef volume (Fig. 24a). In the third case, if sealevel rise considerably outpaces reef growth then the reef will eventually drown.

With the exception of short-lived tectonically-induced pulses of transgression, it is likely, given the growth rate of $\geq 9 \text{ m.1000 years}^{-1}$ suggested by Adey (1978), that over much of the period of reef growth, the rate of sealevel rise has been less than the potential rate of vertical reef accretion. In such circumstances, calcification is largely restricted to the outer margin of the reef edge, resulting in an overall expansion of the reef top area. Subsidence rate interacts with eustatic sealevel change resulting in an overall rate of change of relative sealevel. The decrease in reef size and maturity northwards in the Pulau Seribu is explained by considering the effect of tilting about an east-west axis. The observed pattern of reefs could result from more rapid subsidence of the Seribu Platform in the northern part of the group, and a relatively slower rate of basement subsidence in the south. Figure 28 shows the distribution of small platform and extensive lagoonal platforms reefs in the Pulau Seribu and the east-west axis dividing the areas.

An analogous situation has been described by Grainge & Davies (1983) from the Sengkang Basin carbonates (Section 3.4). Slow subsidence in the south of the basin resulted in build-out of the reefs, and rapid subsidence in the north caused the reefs to build up.

(b) Early development

The shape of the subtidal body - generally elliptical or irregular, is a reflection both of the substrate of nucleation, and of the locally predominant effects of current and wave action which are influenced by neighbouring reefs. Despite the biannual reversal of wind and current direction, the inequality in

strength of the east and west monsoons results in an effective net transport direction which varies from reef to reef and around a single reef. Brown et al. (1982) noted that the northern flanks of reefs are more exposed to and controlled by these physical climatic factors than the southern flanks which are more dominated by competition and biogenic factors.

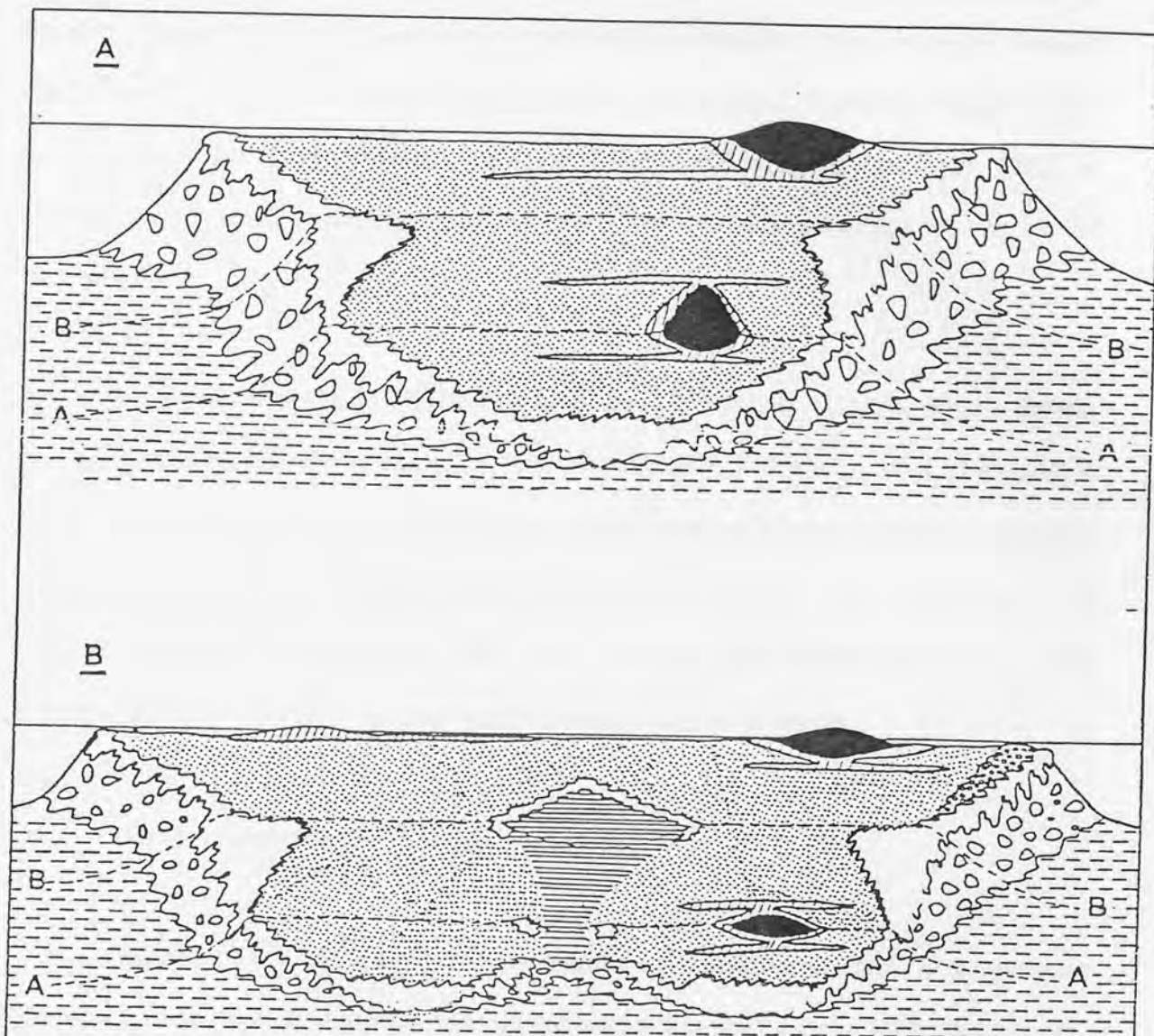
Reduced circulation on the reef top, in exposure to wave action, periodic subaerial exposure, sediment clogging and perhaps exposure to waters diluted by rainfall causes a decline in reef top coral growth and a reef flat environment develops. Under conditions of continuous, if irregular, transgression, the reef flat is maintained by a continual supply of sediment from marginal growth areas, reworked and comminuted by grazing and boring infauna. If sediment supply exceeds sediment loss, supratidal features form. Such a situation will arise as transgression slows or minor regression occurs. Maturing, migration and erosion or drowning of reefs will leave a record in the position of supratidal, intertidal and subtidal sedimentary features which will be revealed by coring through the Pulau Seribu. Figure 25 illustrates a cross-section through a reef formed during a single transgressive cycle and Fig. 26 illustrates the predicted affect of a change in the rate of relative sealevel rise.

The main body of the reef is composed of reef framework and talus generated from the growth areas. The development of the reef flat marks the time at which the growing area reached the level of low tide which thereafter constrained upward growth of the body.

The absorption of energy of shoaling waves at the platform margin results in the piling-up of dead wave-fragmental corals. Coarse debris accumulates and forms a sediment-baffling rampart bordering wave-exposed flanks, resulting in the creation of a protected area in the lee of the debris bank. In Fig. 24 the

Figure 25 - Predicted shallowing-up sequence under conditions of continual gradual subsidence

LITHOLOGICAL COLUMN	DESCRIPTION	FACIES ---denotes gradational contact	INTERPRETED ENVIRONMENT
	<p>Bioturbated shell hash of fine-medium calcarenite. Few visible burrows. Tubular fenestrae.</p>	Carbonaceous	Cay
	<p>Pelloidal rootletted muds. Low faunal diversity. Irregular-laminoid "birdeyes" High organic content and possibly evidence of reduction.</p>	Sparsely bioclastic biotubated pellet-mud	Mangrove colonised mudflats
	<p>Biotubation causing biogenic sorting of sediment. Thin-shelled molluscs in poorly sorted bioturbated sediment.</p>	Coralgal packstone grainstone subfacies	Reef Flat
	<p>Muddy skeletal sands</p>		
	<p>Scattered rubble floating in silty sandy mud. Bioturbated pelloidal mud. Moderate-low faunal diversity increasing upward.</p>	Coarsening upward sequence Sparsely bioclastic bioturbated pellet-mud	Lagoon
	<p>Vague cross-lamination, upward though this may be disrupted by burrows. Coarse branched coral debris, bored and alga-encrusted. Platy corals and abundant algae.</p>	Fining sequence Coral-mollusc-skeletal subfacies Coral cobble rudstone grainstone	Rampart
	<p>Coarse interstitial sediment. Branched and foliose corals. Massive corals. Mixed coral assemblage.</p>	Poorly sorted interstitial sediment Coral-mollusc-skeletal subfacies	Growing Edge
	<p>Floatstone; abraded highly bored coral fragments mixed with open marine faunal assemblage. Silty matrix. Impurity content increases downwards.</p>	Silty clay	Reef-Base grading downward into channel
<div> <div> Carbonaceous sediment rich in organic residue Burrow </div> <div> Rootlet Sand </div> <div> Encrusting algae Branched coral </div> <div> Algal mottling Foliose coral </div> <div> Mud or silty mud Massive coral </div> <div> Mollusc fragment </div> </div>			



A : Effect of a eustatic change on a cay-platform reef

B : Effect of a eustatic change on a lagoonal-cay-platform complex

FACIES

- admixed coral debris-coral-mollusc-algal & coralgal
- skeletal coral mollusc
- silty clay impure carbonate
- sparsely fossiliferous pellet mud
- winnowed grainstone
- carbonaceous

AA-BB marks a period of rapid transgression

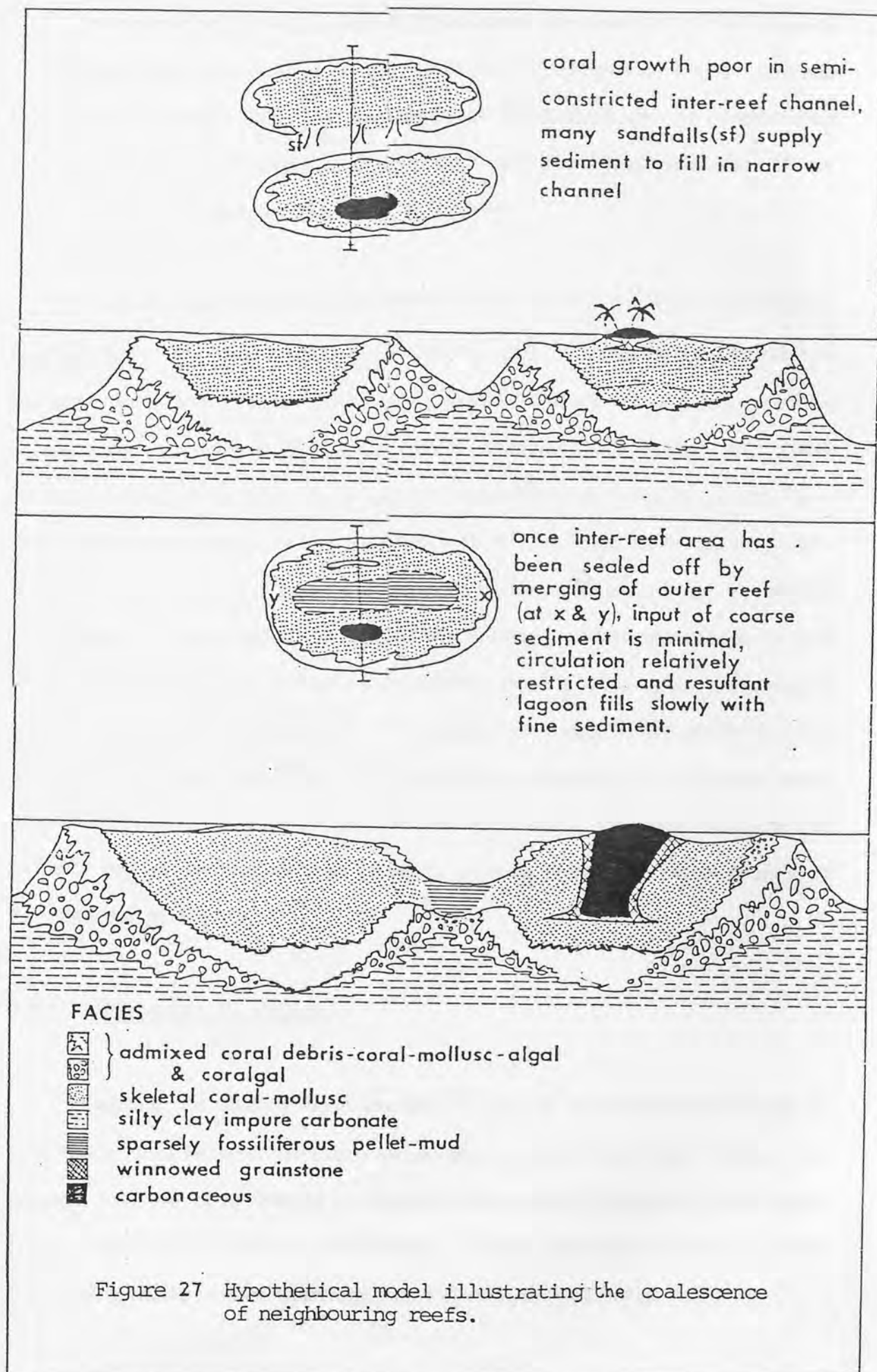
Figure 26 The effect of eustatic fluctuations on reef growths.

shingle rampart is portrayed as a relatively permanent reef margin feature continuously added to at the seaward margin. In contrast, lithified shingle ridges on islands of the Great Barrier Reef are reported (Scoffin & MacLean 1978) to represent individual depositional events and over time are observed to migrate or be eroded.

With one exception (Pulau Ayer, Plate 10) ramparts in the Pulau Seribu are consistently found restricted solely to the shoreward margin of the crestal zone. Storms in this area are frequent and of relatively low strength compared with the gales that lash the exposed Great Barrier Reef. It is considered that shingle ramparts in the Pulau Seribu are created and maintained in the same position relative to other reef zones, by normal climatic events.

(c) Later development

Expansion of the reef is dependent on subsidence rate and eustatic changes. As an apron of reef debris builds out in front of two neighbouring reefs, new stable substrate is created for coral growth (Fig. 28). A colonised leeward bank of reef-derived detritus has formed immediately west of Pulau Belanda almost forming a bridge between this patch reef and Pulau Bira. Similarly a submergent bank has formed east of Pulau Kotok Kecil in the lee of the west monsoon storms to which this reef is exposed. Ultimately continued outward growth will result in merging of the pairs of reefs. Such a situation is considered to have already occurred in the area south of the Pulau Kotok besar-Pulau Bongko line and resulted in the formation of such lagoonal-cay platform reefs as the Pulau Pari complex.



In the north of the Pulau Seribu group, there are a number of reef clusters which should eventually merge to form similar reef complexes if reefs prograde sufficiently laterally. Examples include Pulau Kotok Kecil and the neighbouring submerged reef immediately to the north; Pulau Putri Besar and Kecil (Plate 26b); and Pulau Belanda and the reefs to the west.

The two types of channel discussed in Section 2.3.7 are considered to be related to the evolution of the Pulau Seribu reefs. Islands in the central and northern part of the Pulau Seribu are clustered closely and are separated by narrow type a channels (Fig. 28). These channels and islands form reefal platform areas and each platform area is separated from an adjacent area by a wider and deeper type b channel. In the south of the Pulau Seribu lagoonal-cay-complexes are separated from one another by the wide deep type b channels (Plate 26a,c). This model suggests that the southern reef complexes are the end result of the merging of smaller cay-platforms and the infilling and enclosing of narrow type a inter-reef channels. The embayed reef edge to the north-west and south-west of Pari cay (Figs. 17-19) supports a relatively low diversity coral assemblage compared to other parts of the reef flank. This may represent the point of connection between two formerly separate reefs; that which bears Pari cay, and that to the west.

2.7.3 Alternative Possibilities

Faulting has already been invoked to explain the inferred difference in subsidence rates between northern and southern parts of the Pulau Seribu. It is possible that the close spacing of islands in the north of the group could result from further faulting between the islands. Active faulting may be responsible for causing breaks between such reefs as Pulau Kotok Kecil (Fig. 3 III).

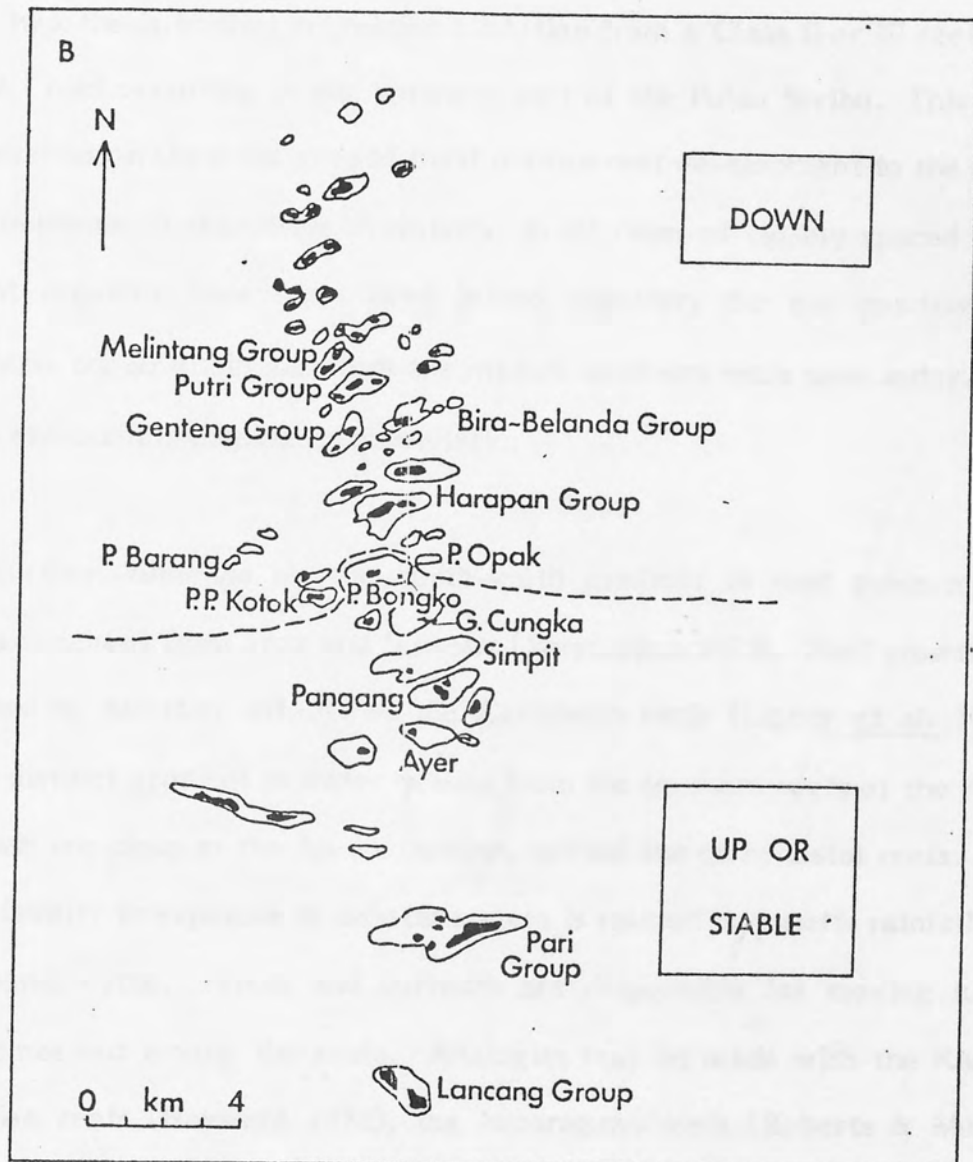


Fig.28 Relationship between northern and southern reefs in the Pulau Seribu and inferred subsidence of the Seribu Platform.

Another possibility for the origin of northern-type islands would involve breaching of the rampart around a large multiple-cay reef complex to form a number of smaller cay-platform and submerged reefs. However, such a rampart breaching hypothesis implies regressive evolution from a Class II or III reef to a Class II or I reef occurring in the northern part of the Pulau Seribu. This is an unlikely progression since the area of most mature reef development to the south shows no evidence of regressive evolution. In all cases of closely spaced reefs that might arguably have once been joined together, the cay position and reef:cay ratio are so dissimilar from the mature southern reefs seen today, that regressive evolution is considered unrealistic.

A further influence on the north-south gradient in reef types maybe terrigenous sediment from Java and Sumatra (Verstappen 1975). Reef growth has been related to turbidity effects in the Caribbean reefs (Lighty et al. 1978). There is a distinct gradient in water quality from the southern reefs of the Pulau Seribu which are close to the Java coastline, toward the more distal reefs. The annual variability in exposure to coastal waters is related to runoff, rainfall and the monsoonal cycle. Winds and currents are responsible for moving turbid coastal plumes out among the reefs. Analogies may be made with the Kasaba and Red Sea reefs (Hayward 1982), the Nicaraguan reefs (Roberts & Murray 1983) where the terrigenous control is strong and with the delta-flanking reefs of the Mahakam Delta near Balikpapan, Indonesia. The Miocene Punung reefs of south-central Java have already been briefly alluded to (Section 2.7.1). The development of these may too have been hampered by clastic flowing southward from the Sunda landmass. Close to the palaeoshore, carbonate deposition is polarised in separate isolated buildups but with increased distance south, the buildups are close together and interconnected by impure limestones (Koesoemadinata, pers. comm. 1983).

Apart from the turbidity effect of locally-derived terrigenous sediment, temperature and chemical changes must have had an effect on reef growth during the Holocene on this tectonically active plate margin. The Krakatoa eruption of 1884 is likely to have had a marked effect on regional water chemistry.

Thermo-chemical changes in the global water systems have been attributed to the strong 1982-83 El Nino (Wyrtki et al. 1976; Philander 1983) event related to upwelling and changes in circulation. The El Nino effect appears to have caused "bleaching" (Glynn 1983) and consequent death of corals over widespread areas of reef slopes in the Pulau Seribu (Plate 16c). Study has shown that elevated nutrient levels, which might be related to upwelling currents, are capable of suppressing coral reef calcification. Millipora and Pocillopora are reportedly the most sensitive genera on the reef (Glynn 1983).

2.7.4 Classification

The most widely quoted reef classifications to date, those of Maxwell (1968) and Hopley (1983), are derived from studies of the Australian Great Barrier Reef. For this reason neither classification is entirely applicable to the Pulau Seribu reefs. Maxwell's (1968) scheme traces the development of an embryonic colony through five stages to maturity (Fig. 29).

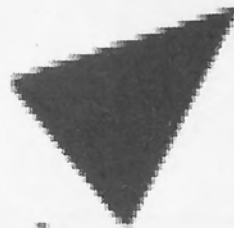
Type I embryonic colony.

Type II platform reef or elongate platform reef.

Type III asymmetric mature elongate platform reef.

Type IV compound closed ring reef.

Type V compound mesh reef complex.



Aston University

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Fig.29

Classification of reef types (adapted from Maxwell 1968).

This classification suggests that extensive lagoons evolve from large enclosed reef flats. Observation of lagoons on a number of southern Pulau Seribu reefs would suggest that mature compound mesh reefs have formed and that lagoons are gradually infilled by marginal encroachment of reef flat sediment (Plate 11e). The ultimate product is an extensive reef flat dotted with sand cays and vegetated islands, as continued sediment accumulates and piles up. This is seen in progress on the Pulau Pari complex where an unconsolidated intertidal sand cay is developing on the western margin of the extensive lagoon north-west of Pulau Tikus and, on the north-east end of the complex, the small cays developing north of Pari cay mark the former position of the partially infilled lagoon north-west of Pari island. The final product of infilling will be a multiple cay platform reef.

Hopley (1983) developed the two-dimensional Maxwell (1968) model, and proposed a refined classification of islands on the Great Barrier Reef, incorporating the three-dimensional geometry of reefs and utilising the documented history of sealevel change in the area. Hopley proposed that lagoonal reefs evolve through the amplification of underlying irregular topography and that subsequent stages of development are distinguished by the infilling of lagoons resulting in a multiple cay platform reef. Dating of reef cap rocks in the Great Barrier Reef supports this hypothesis; the most mature and oldest reefs are those with the greatest proportion of reef surface covered with supratidal sediment. Two geometrical considerations affect this model. Firstly, larger reefs mature at a slower rate than smaller ones because the length of the reef margin, which determines sediment supply, increases incrementally with size, whilst the area of reef flat and lagoon, which represents the sediment sink increases exponentially. Secondly, reefs smaller than 0.5 km in maximum dimension were rarely found to support lagoons due to the rapidity of infilling.

Hopley (1983) suggested a tripartite classification of reefs into:

Reefs with no lagoon; size range 0.25 - 3.25 km (Mean, 1.05 km)

Reefs with a single lagoon; size range 1.25 - 4.25 km (Mean, 2.53 km)

Reefs with multiple lagoon; size range 2.25 - 12.75 km (Mean, 4.93km).

Emphasis is placed on the lagoons as diagnostic evidence to indicate the former presence of depressions in the antecedent platform.

The drawback in applying this scheme to the Pulau Seribu derives from Hopley's emphasis of inherited Pre-Holocene basement topography. As discussed previously, multistorey reef development in the south west Java Sea is unproven. Whilst Hopley's scheme envisages reef form primarily resulting from the underlying karstified Pleistocene substrate and secondarily from lagoon infilling which masks the primary topography, the evolution proposed for Pulau Seribu (Sections 2.7.1 - 2.7.3) visualises variation in reef form resulting primarily from the relative rate of sealevel rise. These differences in approach are rooted in the postulated origin of lagoons.

Given the present evidence, it is possible to develop a simple genetic subdivision of reef types applicable to the Pulau Seribu which is dependent upon the interaction between changing sealevels and potential rate of reef accretion.

Type I	submerged reef
Type II	cay-platform reef
Type III	lagoonal cay platform reef

Type I reefs are relatively immature and have not yet grown up to sealevel. Type II and III reefs are not linked in an evolutionary sequence: Type

III reefs develop in an area of relative stability or very slow subsidence whilst Type II reefs develop where the rate of subsidence is relatively fast but less than the potential growth rate of corals, thereby permitting the development of reef top features after the reef reaches sealevel. Clearly, an increase in the rate of relative sealevel rise could cause Type III reefs to evolve into Type II reefs or vice versa. The predominance of Type III reefs in the south of the area suggests that relative stability has been achieved earlier than in the north.